PHD

A Mixed Reality Approach for In-Process Verification of Large Scale Assemblies

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Award date:
2017

Awarding institution:
University of Bath

[Link to publication](#)

A Mixed Reality Approach for In-Process Verification of Large Scale Assemblies

submitted by

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for the degree of Doctor of Philosophy

of the

University of Bath

Department of Mechanical Engineering

November 2017

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Dedicated to *Papá, Mamá, Hermanita y Carnalito*

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Acknowledgements

“There is no such thing as a "self-made man". We are made up of thousands of others. Everyone who has ever done a kind deed for us, or spoken one word of encouragement to us, has entered into the makeup of our character and of our thoughts, as well as our success.”

George Matthew Adams, writer.

Throughout the course of this research I have been told countless times that a PhD is “I” and that there is no such thing as “We”. It is my firm belief, as George Matthew, that it is the other way around, and that without the help of family, countless friends, colleagues, supervisors, and institutions I would have never reached this stage.

I would like to thank CONACYT from the Mexican government for enabling me to pursue my doctoral studies and which support has been invaluable.

I would like to thank my current supervisors Dr. Vimal Dhokia, Dr. Joseph Flynn, and Dr. Aydin Nassehi for taking me in when I was lost, for the incredible patience, time, humor, encouragement, and guidance. Without you, I would have never even come close of completing this research and most of all this thesis.

I would like to thank Prof Paul Maropoulos for believing in me and providing the opportunity to undertake this PhD and for whom without, this would have not been possible.

I would like to thank Dr. Andrew Francis for his invaluable support throughout this research. You taught me everything I know about metrology. Thank you for your time, patience and friendship. It was a privilege to have worked with you and I am ever grateful for everything I learnt along the way.

I would also like to thank Dr. Wesley Essink for his priceless support throughout the experimental phase of this research. Without your patience, guidance, and knowledge I would have never completed this research in the time frame I had.

Finally I would like to thank my family, Mom, Dad, Brother and Sister. Without doubt the hardest part of this research was being far away from all of you. Thank you for finding a way to always be there, for your incredible support, and love. I would have never had the perseverance, character, and will to take up this challenge and see it through if it was not because of you.

Abstract

Metrology is integral to all manufacturing operations and component generation, as it is used to prove conformance to design specifications. An inspection process that is not designed or executed properly can lead to delayed deliveries and costly repairs. The combination of Mixed Reality (MR) and metrology could lead to immersive metrology (IM), which has the potential to radically change how part inspection is undertaken. By doing so, it may enhance the value adding capability of being able to dynamically inspect a part, in situ.

The aim of this research is to explore the application of MR in metrology-enabled assembly for increasing the availability of knowledge at the time of assembly and inspection. This research presents a case for IM within the context of assembly inspection. A system termed Immersive System for Large Volume Metrology (ISLVM) is proposed to enable the integration of the critical elements of MR and metrology for dimensional inspection of large volume assemblies.

ISLVM was tested with a participant based study in which 72 volunteers with no previous experience with metrology hardware and software were guided through an inspection process with 3 different media. These were a paper manual, a digital manual accessed through a laptop, and a MR headset. The guides explained how to use metrology instruments and software to complete an inspection process on an assembly. The results obtained were analysed, showing that there is a statistically significant difference between all three interfaces. The interface in which the participants committed the least amount of errors with was the MR interface.

The tests performed in this research demonstrated that MR technology can be integrated with current metrology hardware and software. This integration enables the creation of an ISLVM that has the capability of guiding inexperienced users through complex inspection tasks, while committing fewer errors than the current state-of-the-art tools and methods used in industry. Furthermore, this research produced a generic methodology that enables an immersive system to be used in different applications and industries such as manufacturing and assembly processes.

List of Abbreviations

ADM	Absolute Distance Measurement
AR	Augmented Reality
ARAUM	Augmented Reality Authoring for Maintenance
BIPM	Bureau International des Poids et Mesures
BS	British Standard
CAD	Computer Aided Design
CAIP	Computer Aided Inspection Planning
CAM	Computer Aided Manufacturing
CLR	Coherent Laser Radar
CMM	Coordinate Measuring Machine
CNs	Customer Needs
COS	Condition of Supply
DFA	Design for Assembly
DfV	Design for Verification
DFX	Design For X
DMU	Digital Mock-Ups
ERP	Enterprise Resource Planning
GD&T	Geometric Dimensioning and Tolerancing
GLMM	Generalized Linear Mixed Model
GPS	Geometrical Product Specifications
HMD	Head Mounted Display
HPU	Holographic Processing Unit
IEC	International Electrotechnical Commission
IFM	Fringe Counting Interferometer
IM	Immersive Metrology
IS	Immersive System
ISLVM	Immersive System for Large Volume Metrology

ISO	International Organization for Standardization
KC	Key Characteristics
KICs	Key Inspection Characteristics
LCD	Liquid Crystal Display
LCL	Lower Control Limit
LIMA	Laboratory of Integrated Metrology Applications
LSL	Lower Specification Limit
LT	Laser Tracer
LVM	Large Volume Metrology
MAA	Measurement Assisted Assembly
MC	Measurability Characteristic
MES	Manufacturing Execution System
MPM	Metrology Process Models
NPL	National Physical Laboratory
OlML	International Organization of Legal Metrology
PLM	Product Lifecycle Management
QFD	Quality Function Deployment
SA	Spatial Analyser
SDK	Software Development Kit
SMR	Spherically Mounted Retroreflector
SPC	Statistical Process Control
TRWIC	Times, Right, Wrong, Improvement, Conclusions
UCL	Upper Control Limit
USL	Upper Specification Limit
USMN	Unified Spatial Metrology Network
VR	Virtual Reality
V&V	Verification and Validation
WSRT	Wilcoxon Signed Rank Test

Definitions

Except for verification and validation the following definitions have been defined in “Fundamental Good Practice in Dimensional Metrology” (Flack and Hannaford, 2005) by the National Physical Laboratory (NPL).

- **Dimensional measurement:** “It is the measurement of geometric features of an artefact. Where a geometric feature can be the size, distance, angle, form or co-ordinate. The artefact itself may be anything at all - the height of a person, the diameter of a beer barrel, the length of a truck, the radius of a ball and so on.”
- **Accuracy:** “The accuracy of an instrument indicates how well it agrees with the (conventional) true value.”
- **Precision:** “The precision of an instrument refers to the dispersion of measurements.” In other words, the difference there is between the measurements that were taken of a specific dimension with the same instrument.
- **Resolution:** “The resolution of an instrument is a quantitative expression of the ability of an indicating device to distinguish meaningfully between closely adjacent values of the quantity indicated.”
- **Uncertainty:** “The uncertainty of measurement is a calculation made to describe the bounds within which you have every reason to believe the true value lies.”
- **Tolerance:** The tolerance which will be referred to throughout this report will be a “manufacturing tolerance”. This is the range of size specified by the designers, in which a certain component can lie in and still work as intended.
- **Error:** “The error in an instrument is the difference between the indicated value and the known value of some material standard of size (for instance a gauge block).”
- **Verification:** A quality control process used to evaluate if a component, system, or service meets the designed build specifications. (Maropoulos and Ceglarek, 2010)
- **Validation:** A quality assurance process that proves a component, system, or service meets the desired use requirements when designed. (Maropoulos and Ceglarek, 2010)

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1. Introduction

In the 21st century, the information age, the customer now demands greater levels of complexity, which is challenging current manufacturing practices. For industry to remain competitive, it is important for them to question the current procedures and redesign current processes based on new technologies and the mass global connectivity in which we live in today. It is due to these challenges that industry and academia have begun to explore new digital and data-driven methods that could enable smarter assembly (ElMaraghy and ElMaraghy, 2016). Smarter assembly could make it possible to utilise key characteristics and information to enable a faster, more efficient, personalised, and cost effective assembly of complex engineering products.

Metrology is integral to all manufacturing operations and component generation. This can be in the form of traditional hard gauges for repetitive measurement of specified features, through to scanning methods that can capture multiple points on a given part surface. These methods gather information about the part, either to qualify its conformance to a specification or, in the case of reverse engineering applications, to gain new knowledge about the component. Typically, in manufacturing, metrology is undertaken within a quality department or, alternatively, conducted in-process using in situ methods such as on machine inspection (utilising touch trigger probes), photogrammetry or non-contact high-fidelity scanning.

This research will focus on Large Volume Metrology (LVM). LVM is defined by the National Physical Laboratory (NPL) as measurements over a distance of more than 1m, or when the metrology hardware and software has to be brought to the component being inspected (NPL, 2017). Depending on the level of quality required for the assembly, the inspection procedures can be complex, lengthy and expensive, especially where high quality is necessary. This is due to the unique set of knowledge and training that the users need to have in order to perform correct inspections. For example, the operator must have the ability to control the position and dimensions of key components within limits as low as tens of micrometres across a large volume. They must also be competent with state-of-the-art metrology equipment (LUMINAR and EURAMET, 2016).

In parallel to developments in metrology, augmented reality has reached a maturity that allows it to be used within a manufacturing context. This new emerging technology enables the user to experience a richer and more immersive experience when interacting with their environment.

Currently there exists three terms related with a “Reality” expression. These are Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). A brief explanation of each technology is provided below:

- **Virtual Reality (VR):** This technology presents an imaginary world to the user, or a digital content based on real-world footage. Regardless of what is presented, the user is isolated from the real world and is left to interact with the digital content that is presented (Foundry, 2016). VR aims to trick the brain into believing it is somewhere it is not (Johnson, 2016), which has been one of the hardest challenges the technology has faced.
- **Augmented Reality (AR):** Enables the user to see a digital layer of information overlaid on the real-world environment (Charara, 2015). The user can still see the real-world and it is being enhanced by computer generated input such as sound, video, graphics or GPS data (Foundry, 2016). In general, AR allows the user to see both synthetic light as well as natural light bouncing off objects in the real world (Johnson, 2016).
- **Mixed Reality (MR):** MR is the newest of the three and is similar to AR in that there is a superimposition of digital information in the real-world. However, the main difference is that the synthetic content is able to interact and react to the changing circumstances of the real-world in real time. In MR, the real and virtual worlds merge to create new environments where the physical and digital objects interact and co-exist in real time (Kay, 2017).

Within an engineering context, augmented reality is being used to help engineers design more efficiently using a combination of interaction and immersion within dedicated computer aided design environments. New technologies such as the Microsoft HoloLens (Microsoft Hololens, 2017) are being used to help designers realize new ways to design and collaborate. Figure 1 shows an example of two engineers with a HoloLens in which they are collaborating on a design of a new robotic arm, while manipulating a hologram of the prototype in the factory environment.

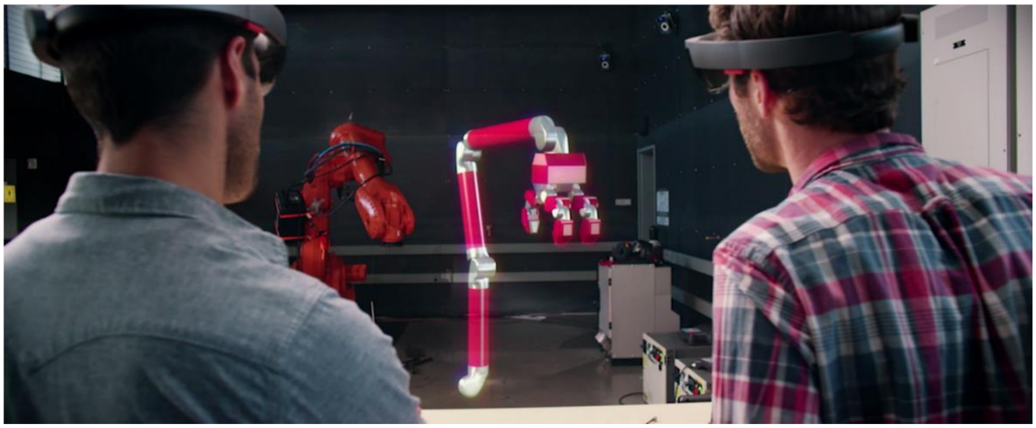


Figure 1 - Collaboration between engineers with the Microsoft HoloLens (Microsoft Hololens, 2017)

Currently, AR tools are starting to be used to aid operators in the assembly process (Syberfeldt, Danielsson and Holm, 2015). These tools display, on the part or on a nearby screen, step-by-step instructions on how to assemble the parts that the operator has in front of them. It has been proven that current AR tools reduce assembly times, operator errors, increase efficiency, working memory, and reduce the learning curve for novices when used for training (Wang, Ong and Nee, 2016). However, after the assembly has been completed, these parts still have to go through a lengthy verification and validation process. At present, there are limited AR tools that perform verification either at the time of manufacturing or assembly of a component (Yamauchi and Iwamoto, 2010; Odenthal *et al.*, 2014). Despite its promise, the use of AR for verification and validation procedures has been limited and its potential impact is not well understood.

This research explores the impact of MR technologies in manufacturing and assembly processes. In particular, it focuses on the user performance as a result of increasing the availability of key knowledge throughout metrology and assembly procedures. In a metrology context, MR methods could enable a more streamlined and efficient way to conduct part measurement and inspection of assemblies. The combination of mixed reality and metrology has the potential to radically change how part inspection is undertaken and, by doing so, enhance the operator’s ability to dynamically inspect a part, in situ, without the need to handle it. It will be necessary to overcome current challenges, such as a seamless integration of MR software and hardware with the metrology software and instruments. To the best of the author’s knowledge, the combination of MR and metrology technologies, as well as their full integration to study the effects of user performance in assembly verification and validation, is a combination of factors that has not been researched before. In this thesis, the combination of mixed reality and metrology for large volume applications has been termed *“ISLVM”* for Immersive System for Large Volume Metrology.

In this research, an immersive system that utilises state-of-the-art MR and metrology equipment and practices is presented. This system and its effect on user performance is tested with a participant-based experiment in which 72 volunteers completed three tests. Each of these tests exploits a different interface: a paper manual, a digital manual accessed through a laptop, and the Microsoft HoloLens, which is one of the newest AR technologies. The data gathered from these tests is used to evaluate the potential of the ISLVM and answer the proposed research questions.

1.1 Research Aim and Objectives

The aim of this research is to study the application of MR in metrology-enabled assembly for increasing the availability of knowledge at the time of inspection, and measure user performance against current best practice.

In order to achieve this aim, the following objectives are outlined:

- To review the state-of-the-art in metrology, in-process verification, and the use of augmented reality in manufacturing, particularly as a tool for verification and validation.
- To specify and design an ISLVM for increasing the metrology information availability at the time of assembly and inspection of a product. This objective can be completed by:
    - Defining the metrology information requirements at the time of assembly of products.
    - Find a suitable MR technology that is capable of displaying the information defined above, while seamlessly interacting with the metrology hardware and software, and provide the user full visibility of their surroundings with a hands-free experience.
- To design experiments that demonstrate the suitability of MR for verification and validation, in which, ISLVM can be tested and put under varying industrial inspired circumstances to assess performance.
- To establish a generic methodology that would enable the deployment of an immersive system to other areas such as manufacturing and assembly processes.

Based on the aim and objectives, the research hypothesis is:

The use of an MR system in the verification and validation process of assemblies will enable a single operator without metrology expertise, to complete a full inspection process while committing fewer errors than paper based and digital methods. This will result in a documented inspection process undertaken by operators on the assembly line and not by an expert metrologist.

1.2 Thesis Structure

The thesis is divided into 8 chapters. Chapter 1 is an introduction to the research and presents the research aims, objectives, and hypothesis. Chapter 2 is a review of the existing literature on metrology, verification and validation (V&V), measurement-assisted assembly, and the use of AR in manufacturing, assembly, and verification. The research gaps are identified and explained in this chapter. Based on this analysis, Chapter 3 introduces the scope, context, boundaries, and methodology of the research. Chapter 4 proceeds to specify the ISLVM. This then leads into Chapter 5, which details the experimental phase of the research, and how the ISLVM is evaluated. Following this, the results obtained from the 72 participants in the experiment are analysed and presented in Chapter 6. Then, Chapter 7 discusses the research findings and limitations in order to formulate the conclusions and future work found in Chapter 8.

2. Literature Review

2.1 Introduction

As specified in the introduction, this research focuses on Large Volume Metrology (LVM). Therefore, the review of concepts, methods, standards, and instruments in this chapter predominantly covers systems used within LVM.

This chapter is divided into two sections. The first section focuses on the fundamental aspects, case studies, trends, applications of measurement, and verification and validation (V&V) within the context of LVM. The second section provides a review of Augmented Reality (AR) and its use in manufacturing, assembly, and verification to identify its potential use in metrology. Figure 2 shows the structure of the main Literature Review. A further section representing the critique of the literature is provided in 2.7

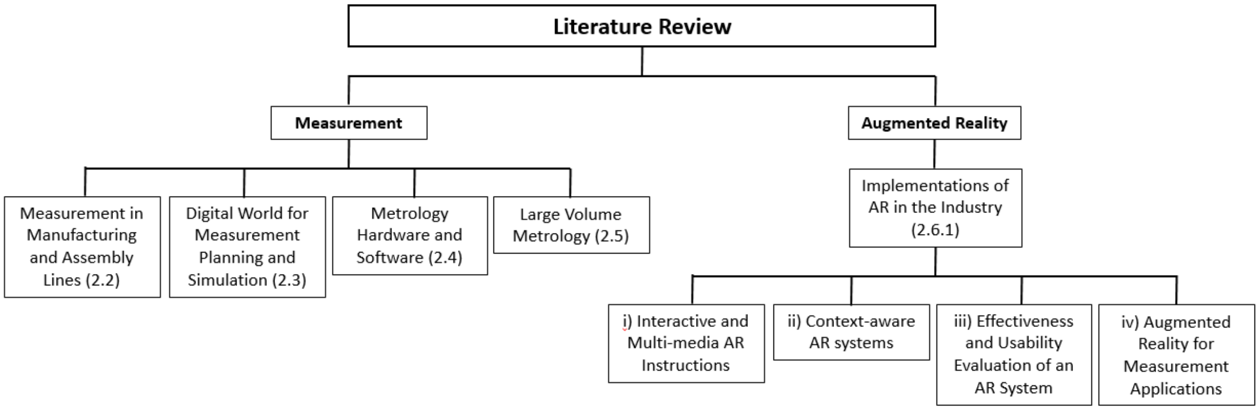


Figure 2 - Structure of the Literature Review

2.2 Measurement in Manufacturing and Assembly Lines

There can be several reasons why a dimensional measurement is undertaken and these depend on the application. In the case of manufacturing, one of the ways in which a company can know if their product is accurately manufactured and assembled is through making dimensional measurements. Measurements are also used as evidence of agreement or disagreement with the stipulated specifications. Furthermore, having accurate dimensional measurements allows commercial and research entities to monitor and control the variations that are unavoidable in any manufacturing system (Flack and Hannaford, 2005).

By applying appropriate measuring techniques, it is possible to manage the inherent variation in a manufacturing and assembly line. The aim is to control, predict or maintain the variation within a certain range that allows the parts to function as designed. One of the most widely used methods used for this is called *Statistical Process Control* (SPC). The aim of this method is to reduce variation by applying a statistical approach to the manufacturing process (Flack and Hannaford, 2005). This method works by inspecting a specified number of parts or assemblies, and then plotting the results of the inspection on a graph over time in which the specifications limits are marked. Using this method, it is possible to predict when a part is likely to fall out of the specified tolerance limits and make adjustments to the manufacturing process. The number of parts inspected depends on the quantity of items produced, and how safety critical they are. Figure 3 provides an example of a typical SPC chart.

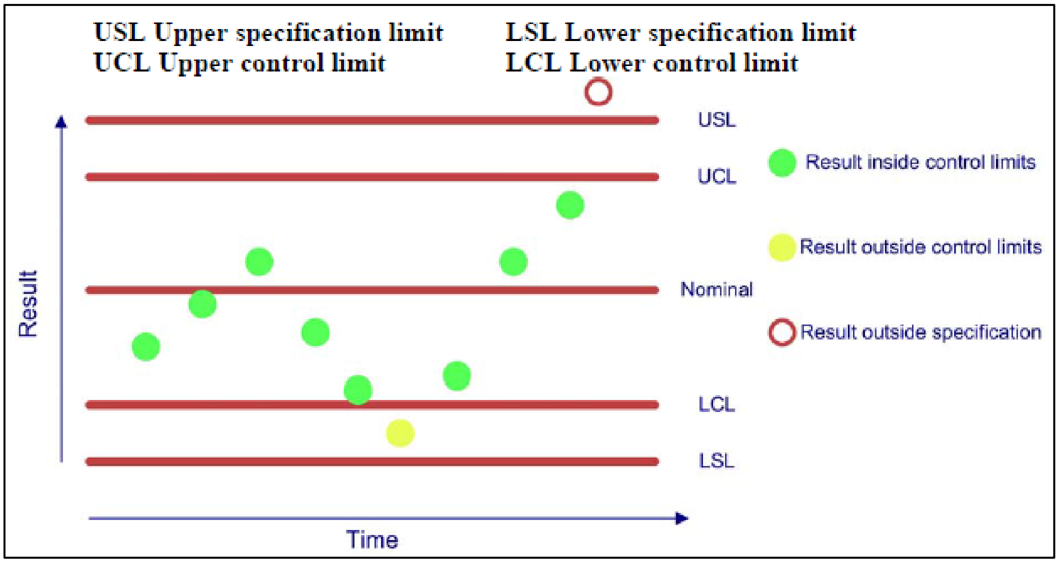


Figure 3 – Statistical control chart example. (Flack and Hannaford, 2005).

i) Uncertainty

Uncertainty of measurement is a parameter that is related to the possible error in the estimated value of a measurement taken (JCGM, 2008). This can be seen as the quality of the measurement (ISO 14253-2:2011, 2011); the lower the uncertainty is, the better the measurement is.

There are four different types of errors that a measurement can have.

- Systematic errors: These errors repeat and are the same from one measurement to another. However, all errors are, by nature, systematic. When an error is considered non-systematic, it is typically due to a lack of resolution, or because the source of the error has not been identified. A systematic error can be calculated by:

$$\mathbf{ER = MR - TV} \qquad (1)$$

Where ER is the error, MR is the measurement result, and TV is the true value.

- Random errors: These are systematic errors that are caused by non-controlled random influence quantities as defined by ISO (ISO 14253-2:2011, 2011).

- Drift: A drift error is the same as random error, which is caused by a systematic influence of factors that cannot be controlled. These errors are normally a time effect or a wear effect (ISO 14253-2:2011, 2011).

- Outliers: These errors are caused by non-repeatable incidents in a measurement. Examples of these type of errors are noise and human errors such as misreading of an instrument or mishandling of a measurement device. Due to the nature of these errors, outliers are impossible to characterise in advance.

As can be deduced from the above definitions, errors or uncertainties in a measuring process will be a combination of known and unknown sources. ISO (ISO 14253-2:2011, 2011) has determined 10 different sources that can individually or collectively have an impact on a measurement. These 10 sources can be seen in Figure 4.

Figure 4 - Uncertainty components in measurement (ISO 14253-2:2011, 2011).

Once all of the systematic effects have been taken into account and the corresponding corrections have been made, there will still remain uncertainty due to random effects and an imperfect correction for the results of systematic effects. Therefore, an overall uncertainty needs to be calculated. The overall uncertainty estimate gives a numerical assessment of the reliability of the result. This in turn enables users to compare results on the same basis (Flack and Hannaford, 2005).

It is therefore important to obtain this overall uncertainty estimate which is called Expanded Uncertainty. To be able to obtain this value an Uncertainty Budget needs to be made.

The value of a measurement is typically composed of several inputs. In order to obtain the expanded uncertainty, it is necessary to first obtain the individual standard uncertainties associated with each input. Once these are obtained, they need to be classified in to either Type A or Type B uncertainty.

- **Type A:** Uncertainties that are obtained through statistical methods.
- **Type B:** Uncertainties obtained through other means that are not statistical. These can be obtained from the following sources or procedures:
    - “*Previous measurement data on the same or similar system.*
    - *Manufacturer’s specifications.*
    - *Figures from calibration certificates.*
    - *Uncertainties associated with reference data from handbooks.*
    - *Previous experience with the behaviour of certain instrumentation.”*(Flack and Hannaford, 2005)

The formula used to calculate the uncertainty propagation is called the variance formula and is the following:

$$s_f = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 s_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 s_y^2 + \left(\frac{\partial f}{\partial z}\right)^2 s_z^2 + \cdots} \qquad (2)$$

Where s_f represents the standard deviation of the function f , s_x represents the standard deviation of x , s_y represents the standard deviation of y , and so forth.

However, the standard uncertainties can be squared, added up, and then perform a square root on this addition in order to obtain the combined standard uncertainty. The formula is the following:

$$u_c(x) = \sqrt{(u_1(x))^2 + (u_2(x))^2 + (u_3(x))^2 + \ldots} \tag{3}$$

Where $u_1(x)$, $u_2(x)$ and $u_3(x)$ are Type A and Type B standard uncertainty components.

Once the combined standard uncertainty is obtained it is possible to calculate the expanded uncertainty. This is calculated by multiplying the combined uncertainty by a coverage factor (k), where the value of k for a confidence level of 95% is 2 (Flack and Hannaford, 2005).

As stated previously, one of the main reasons why a measurement of a feature is taken is to see if it complies with its specification. Hence, it is crucial to know the uncertainty of the instrument that is being used to take the measurement, otherwise it is not possible to know if the part being measured is inside the tolerance range (Cai *et al.*, 2009). To help with this issue, a comparison of the tolerance zone with the stipulated uncertainties from the measurements can be performed before any measurements of the verification process take place. This is explained in Figure 5 and the explanation below:

> **A.** The red line represents the uncertainty band of the measurement. As can be seen, this uncertainty is greater than the tolerance allowed by the component. Although the reading is inside the tolerance zone it will not be possible to determine if the component is within tolerance or not due to the uncertainty band being larger than the tolerance zone.
>
> **B.** The reading shows that the part is outside of the tolerance zone, and the uncertainty band is small enough that there is no overlap between the uncertainty and the tolerance. Hence, it can be stated with confidence that the part is outside of tolerance, and this is the only time when the customer can reject a part.
>
> **C.** The reading shows that the part is out of tolerance and the uncertainty band is smaller than the tolerance zone. However, there is an overlap between the uncertainty band, and the tolerance zone. The part could be in tolerance but this cannot be stated with confidence due to the overlap, thus it must be rejected.
>
> **D.** In this reading, the part is in tolerance and the uncertainty band is less than the tolerance of the part. However, as in the previous reading, there is an overlap between the uncertainty band and the tolerance of the part. Therefore, it cannot be stated with confidence that the part is in tolerance, and must be rejected.

E. In this instance the reading shows that the part is in tolerance and the uncertainty band is less than the tolerance of the part. Furthermore, there is no overlap between the uncertainty and the tolerance. Hence, it can be stated with confidence that the part is within tolerance. This is the only scenario in which a supplier can prove conformance.

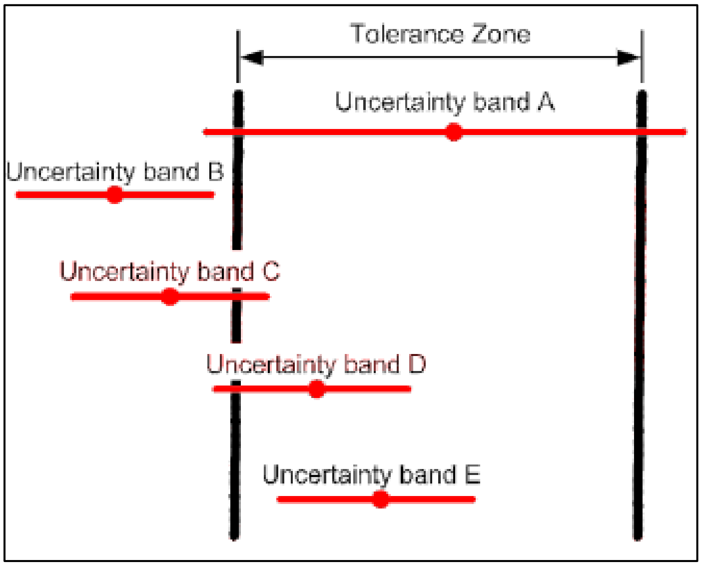


Figure 5- Possible interactions between Tolerance Zone and Uncertainty Band (Muelaner, Cai and Maropoulos, 2009).

As can be seen from the previous example, it is important for suppliers to be aware of the uncertainty and reduce it as much as possible as a larger uncertainty can result in a higher ratio of rejected parts.

ii) Standards in Metrology

International standards play a key role in being able to ensure consistent product quality through the supply chain. This is achieved by stipulating a standard procedure or method in which a certain process should be performed. This in turn enables the comparison of a result to a generally accepted procedure that has previously been agreed upon by the leading entities of the respective field.

Although there is no current standard for LVM, there are several other standards and guides that are used in metrology. The most recognised standards and guides that are relevant to this research are detailed below:

- Evaluation of measurement data — Guide to the expression of uncertainty in measurement (JCGM, 2008)**:** This standard is one of the most used standards in metrology. It was developed by the Joint Committee for Guides in Metrology (JCGM). This committee is composed of experts nominated by the Bureau International des Poids et Mesures (BIPM), the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the International Organization of Legal Metrology (OIML). All of the other guides on measurement uncertainty stem from this standard. The main purpose of GUM is to set a *readily implemented, easily understood, and generally accepted procedure for characterizing the quality of a result of a measurement, that is, for evaluating and expressing its uncertainty* (JCGM, 2008). Therefore, this standard establishes general rules for evaluating and expressing uncertainty in measurement that are aimed to be used in a wide variety of measurements.

- BS EN ISO 14253-2:2011 (ISO 14253-2:2011, 2011)**:** Geometrical product specifications (GPS)- Inspection by measurement of workpieces and measuring equipment, Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification. This standard was defined by ISO and has also been accepted as a British Standard (BS). This standard is a simplified and iterative procedure derived from GUM to calculate the standard and expanded uncertainty, as well as make recommendations on how to document and report the uncertainty of measurement. The standard explicitly states that this simplified procedure can save time; however, it can lead to a slight overestimation of the uncertainty of measurement. If a more accurate estimation is needed, then the full process outlined in GUM should be followed.

- A National Measurement Good Practice Guide No. 80 – Fundamental Good Practice in Dimensional Metrology (Flack and Hannaford, 2005)**:** The purpose of this guide is to present an overview of good practice and measurement techniques at an accessible technical level. The intention of this guide is to introduce key concepts to readers, enabling them to make better measurements.

- ASME Y14.5 Geometric Dimensioning and Tolerancing (GD&T) (American Society of Mechanical Engineers., 2009)**:** This standard is considered to be the authoritative guideline for the design language of GD&T. It establishes uniform practices for stating and interpreting GD&T and related requirements for use on engineering drawings and in related documents. The main purpose of GD&T is to be able to communicate the design intent in a uniform and unambiguous way that reduces the guesswork in the manufacturing and assembly process. As a result, it helps to improve quality, reduce costs and reduce manufacturing or assembly times. This standard is important for metrology due to its impact and influence in tolerancing. If tolerances are not well defined, nor communicated then the verification procedure is likely to be complex and time consuming. This is due to the absence of a clear reference to measure against, compare the results to, or identify unnecessarily tight tolerances that cannot be fulfilled by the suppliers.

- **ASME B89.4.19 – 2006** (ASME, 2006)**:** Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems. This standard describes the methods used to evaluate the performance of laser trackers and provides a basis on which such systems can be compared. These tests are designed to evaluate the point-to-point length measurement capabilities of laser trackers.

- **NPL Laser Tracker error determination** (Hughes *et al.*, 2011)**:** This paper is entitled "Laser Tracker error determination using a network measurement". This method provides a fast and easy way to determine all of the geometrical alignment errors of a laser tracker to a high degree of precision. It requires no specialized equipment and can be performed in less than an hour. This method is a quicker alternative to the B89 standard.

Standards, if used correctly, can be useful in obtaining a well-defined and stipulated metrology plan, manufacturing, and assembly process. The standards or guide to be used depend on the process, stage of assembly, and area that is being worked in.

2.3 Digital World for Measurement Planning and Simulation

Currently, most of the design of a new product, service, assembly, or system is undertaken digitally. Digital models enable manufacturers and designers to visualize parts and processes that can aid in identifying potential problems, conflicts or new ways to design the part. The value of these simulations depend on the time, detail, and specification in which they are made. The more time, and detail that is put into the digital models and simulation, the more realistic the results will be. Thus, it is possible to use a validated digital prototype as a reference to which the manufactured products can be compared (Maropoulos and Ceglarek, 2010).

These prototypes are generally called Digital mock-ups (DMU). DMUs have become an important design collaboration tool in which different teams across a company can simulate and verify a product through its entire lifecycle. This includes production planning, performance of the component, maintenance, and in some cases recycling (Worn, Frey and Keitel, 2000; Wang, 2002).

Due to the recent growth in the availability of enhanced computer resources, companies have started to increase the use of DMUs, obtaining positive results. For example, Chrysler used DMUs to reduce automobile cycle development by one half, and resolve 1200 potential issues before the first physical mock-up was built. Another example is Boeing. By using DMUs, they were able to reduce errors and reworks on the 777 airliner by between 70–80%, saving 100,000 design hours which translated to considerable monetary savings (Rooks, 1998). From these examples, it is clear to see the efficiency and financial benefits of a well-defined and made DMU.

When the design team begins the DMU they must include part and assembly tolerance setting and specification. This step can have an economic impact as well as influence on the final metrology plan. The reason being that if the tolerances that are being set are too tight, then this will add cost as there will be a requirement to use more accurate equipment, as well as more time consuming and complex verification procedures. On the other hand, if the tolerances are too light, this could result in "scrapped" parts that will not perform as stipulated in design specification. In order to prevent this, there are Computer Aided Tolerance systems that model the effects of tolerance setting in a manufacturing or assembly process. These simulations include the analysis of tolerance build-up and potential assembly clashes within the DMU (Maropoulos and Ceglarek, 2010).

The tolerance design methods are summarized in Figure 6:

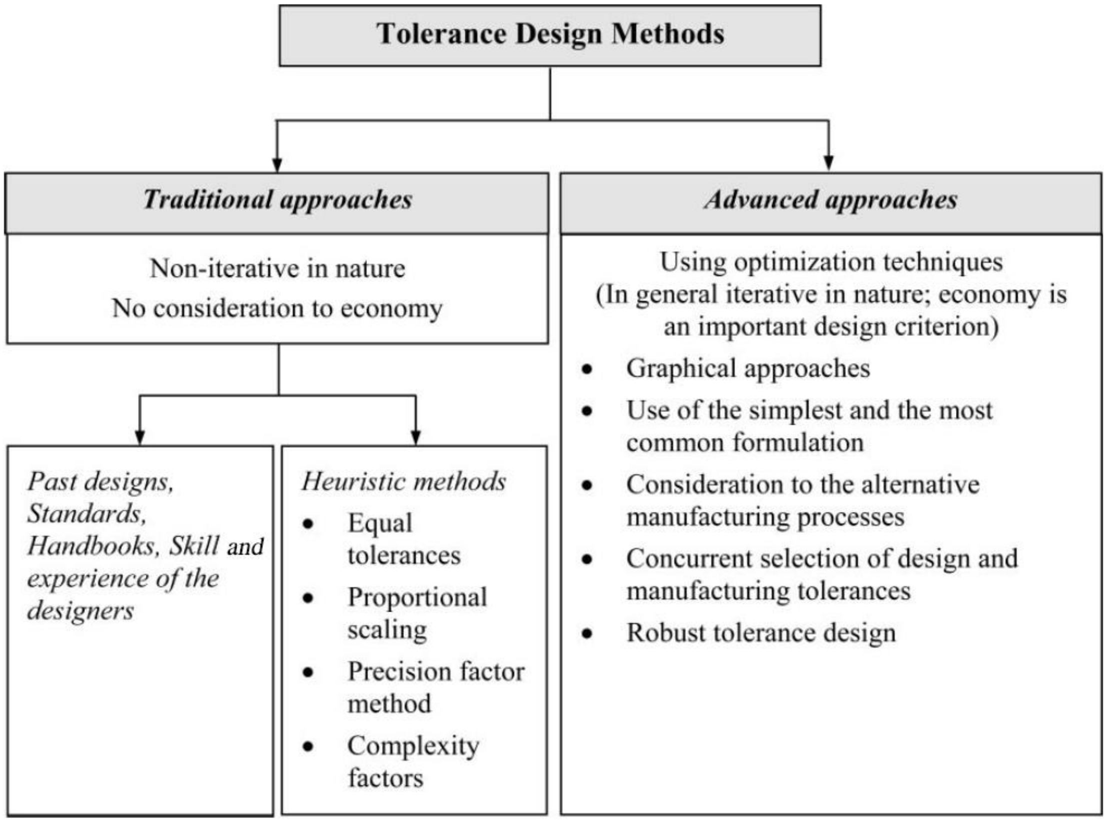


Figure 6 - Tolerance design methods (Singh, Jain and Jain, 2009).

Currently, measurement plans are integrated within the design and manufacturing plan, thereby increasing the likelihood of completing a successful inspection process (Zhao, Xu and Xie, 2009). To organize and simplify the planning of the inspection process Lee et al. (2004) split the measurement process planning into two categories:

1) **Global inspection planning:** This section is aimed at trying to obtain the best inspection sequence possible for the manufacturing and assembly process.
2) **Local inspection planning:** This stage attempts to reduce the measurement time and the errors that could arise from the inspection process.

To help with the inspection planning process even further, there have been several computational platforms developed that can assist with the measurement planning task. The following segments from (Maropoulos and Ceglarek, 2010) provide a brief summary and define Computer Aided Inspection Planning (CAIP):

- The procedure followed by CAIP to complete the measurement planning task consists of the following 5 generic steps: 1) Detection and recognition of the CAD interface and features, 2) establishing the sequence in which these features will be inspected, 3) determination of the number of points to be measured and their locations, 4) establishing the measuring paths, and 5) carrying out of the simulation and verification of the measurement plan.
- The research that is conducted in CAIP falls mainly within two categories: 1) tolerance-driven inspection process planning, and 2) geometry-based inspection process planning. The first category inspects features that have specific tolerances assigned to them, while the second category compares the complete geometry of the part or assembly against the design model.

Furthermore, Maropoulos et al. (2008) developed a theoretical framework for the development of metrology process models (MPM) for integrating product design with assembly planning. This MPM enables the creation of a measurement assisted assembly process that considers process capabilities, tolerances, constraints, instrument selection, implementation and deployment, and data reference section. Figure 7 explains the framework for this MPM followed by a more in-depth explanation of the stages of this model.

1) This section evaluates the design models by comparing the GD&T specifications of the components and assemblies with the capabilities of the measurement systems.
2) This section integrates measurement planning with tolerance analysis and assembly planning.

3) *A deployment characteristics section, including instrument specific set-up and calibration procedures and methods for interfacing a metrology system with process automation. Generic methods that consider environmental parameters and algorithms for reducing uncertainty during measurement are also included in this functionality section of the metrology process models. This functionality integrates LVM methods with real assembly environments and supports their real-time deployment.*
4) This is a data reference section, in which available international standards help manage the collection of dimensional results and their use by reporting applications, such as SPC.

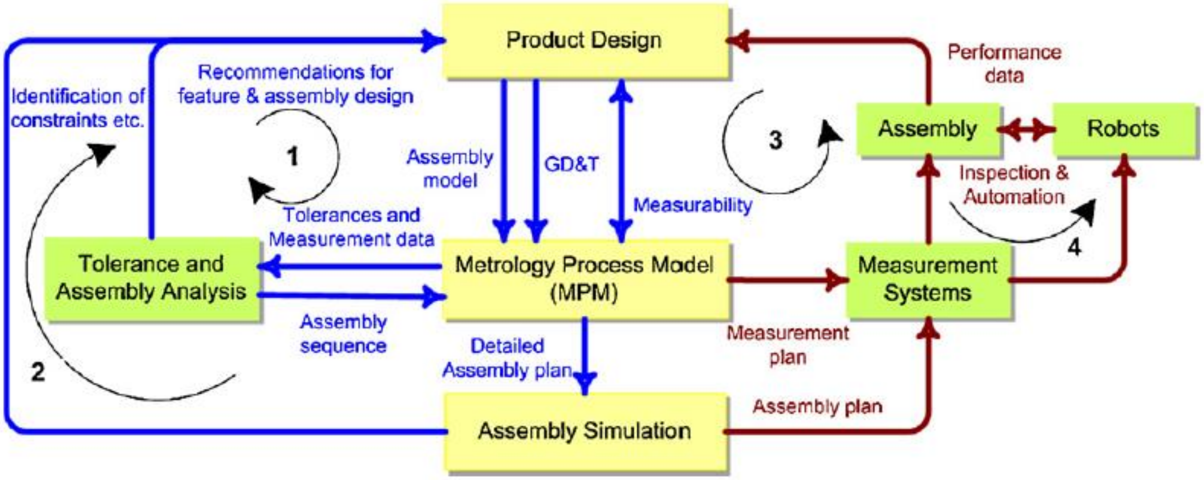


Figure 7- A framework for integrating measurement with assembly planning (Maropoulos *et al.*, 2008)

Also, as an aid to establish an adequate inspection process, Cai et al. (2009) developed an instrument selection tool that has been designed using Measurability Characteristics (MC) such as physical capability, uncertainty capability, costs, and technology readiness level. The tool uses a matrix mapping approach for measurement instruments together with an optimization algorithm for solving the combination of multiple measurement aims and measurement instruments.

Although Section 2.4 will describe in detail the use and applications of Augmented Reality (AR), below are examples that introduce how Virtual Reality (VR) and AR have been used as digital tools to enable manufacturing, assembly, and verification processes:

Pappas et al. (2006) used VR methods and tools to evaluate the performance of human-related aspects in an assembly process, thus reducing the amount of physical experimentation hours.

Chryssolouris et al. (2000) developed an VR-based simulation environment to be able to validate process experimentation and verification of factors that cannot be described analytically; thus impacting the process in a non-predictable way. Furthermore, in 2004, they used a hybrid immersive interaction technique and digital mannequin technologies in a simulation environment to be able to further evaluate the assembly performance over a range of different human populations (Chryssolouris *et al.*, 2004).

An Augmented Reality (AR) based human-computer interface was developed by Ong et al. (2007) to provide an immersive and intuitive environment in which they were able to manipulate the virtual prototypes in the real assembly environment. This helped to reduce the possibility of redesigning and re-planning. Brough et al. (2007) developed a Virtual Training Studio (VTS) that was well accepted by the users, and it proved to effectively train workers for assembly processes.

The digital tools and methodologies mentioned in this section, if used correctly, can enhance the design process of a new part during its lifecycle within the context of a digital domain. This can result in quicker design, improved accuracy and performance, cost reduction, and less variability.

The following diagram is a framework presented by Maropoulos et al. (2010) that summarizes the verification and validation that takes place in the design phase as well as the physical stage of a product.

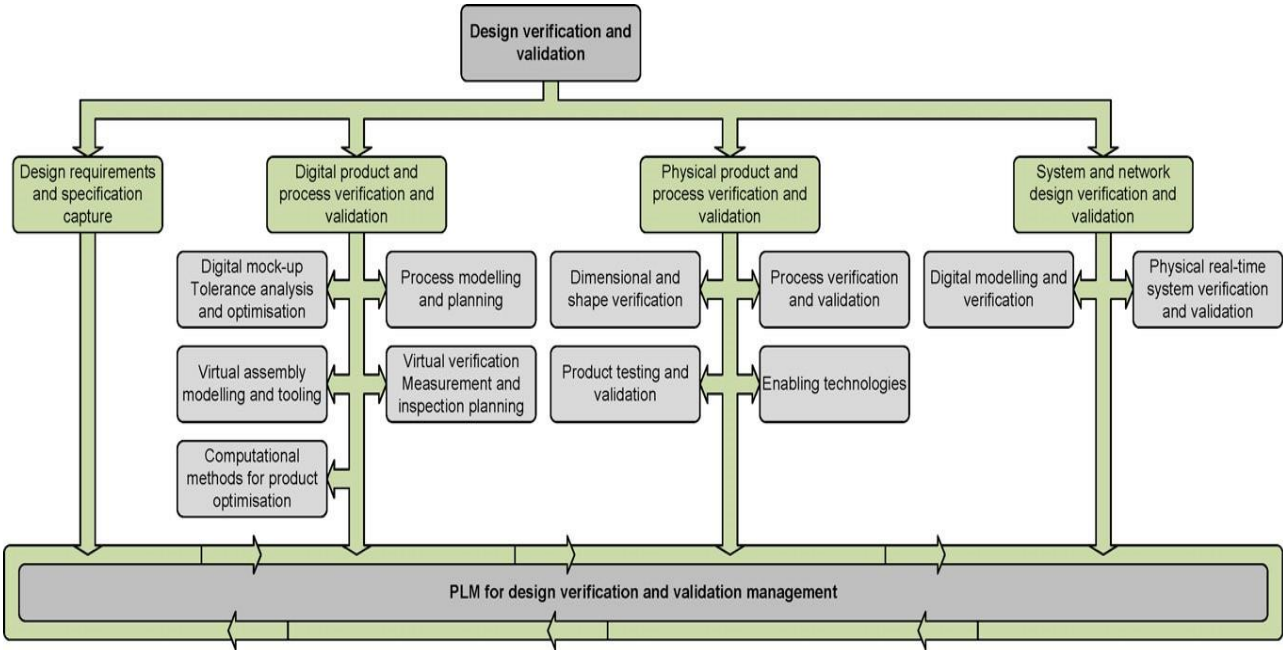


Figure 8- A framework for design verification and validation (Maropoulos and Ceglarek, 2010)

To achieve verification and validation in the physical stage of the framework presented above, it is necessary to use metrology hardware that can help the user measure the specified parameters and compare the results to the client's specifications.

2.4 Metrology Hardware and Software

This section reviews with metrology equipment and software that is currently used in LVM. Explanation of how they work, advantages and disadvantages of the technologies, and finally applications of these tools are presented. The descriptions of the equipment are supported by theory and images that clarify how the metrology equipment works.

2.4.1 Laser Based Spherical Coordinate Measurement Systems

There are two types of measurement laser systems:

- Laser Trackers
- Laser Radar

Although only Laser Radars are non-contact, both technologies are considered to be non-invasive verification systems. In the following sections both technologies will be reviewed and discussed.

i) Laser tracker

The laser tracker has been the instrument of choice in large volume metrology when it comes to high accuracy product conformance verification, tool setting, and jig verification (Francis *et al.*, 2016). Within laser trackers there are two types of systems used for high precision measurements. These are a Fringe Counting Interferometer (IFM), and an Absolute Distance Measurement (ADM) system. The oldest and most accurate (Airbus and Bath, 2010) is the IFM. However, the ADM system has continuously been developed and improved, and is currently one of the most accurate measurement technologies available, with an accuracy of approximately 15 µm (FARO, 2017). Due to its ease of use and that it allows faster target measurement, ADM systems are currently the most popular type of laser tracker. This has led to some brands considering a cease in production of IFMs altogether (Wright, 2016). Below an explanation and applications of these systems are presented.

- Interferometer (IFM)

Inside the laser tracker, a frequency-stabilized laser emits a laser beam. This beam is then split in two by a beam splitter. One beam is directed into the interferometer. The other beam leaves the tracker, reflects off a target placed at the point of inspection (usually a spherically mounted retroreflector (SMR)) and is reflected back into the interferometer. Inside the interferometer, the two beams then constructively or destructively interfere with each other (Bridges, 2009). This results in a cyclic change each time the SMR moves by a distance equal to one quarter of the light's wavelength (approximately 0.0158 microns). A detector inside the interferometer counts the cyclic changes, which are known as "fringe counts", to determine the distance travelled by the laser beam (FARO, 2009). In order to be able to calculate a 3D point in space a laser tracker has two angular encoders. These measure the angular orientation of the tracker's azimuth and elevation. The combination of the distance measurement and the two angular encoders is what provides an accurate 3D coordinate measurement. Figure 9 provides a pictorial representation of how an IFM laser tracker works.

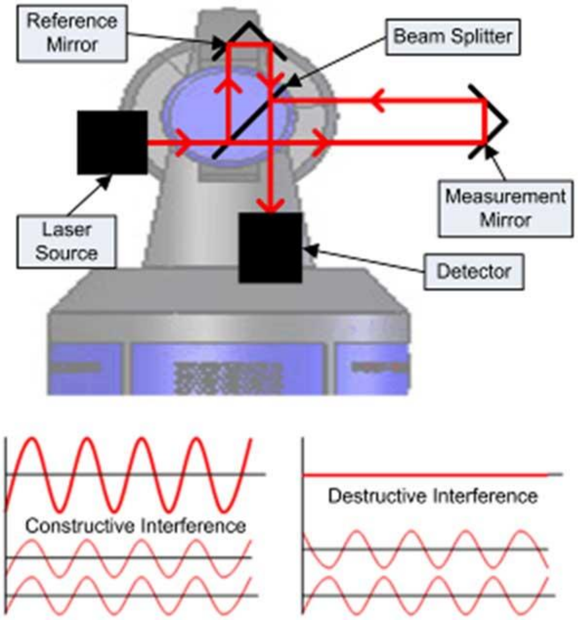


Figure 9- Illustration representing how an IFM Laser Tracker works (Muelaner, 2015)

The SMR has to be placed in a reference or "home" position prior to the start of the measurement. Then from there the user can take the SMR and position it in the desired place for measurement. As soon as the SMR leaves this home position the fringes are counted. In the event that the beam is disturbed or is broken from the SMR due to an obstruction on the assembly floor or due to an operator error, the count of the fringes are lost, and the measurement has to be restarted from the home position. This can cause the measurements to take considerable time to be completed. This is the main disadvantage of this technology and has caused some users to instead use an ADM Laser tracker, despite the IFM achieving higher accuracies (Airbus and Bath, 2010).

- Absolute Distance Measurement (ADM)

The major difference between an ADM and an IFM is that the former will give as a result, a distance instead of a displacement. This permits the beam to be broken or interrupted while in the production floor without needing to restart from a home position.

An ADM system works by using a time of flight approach. Infrared light from a semiconductor laser inside the ADM system is emitted and reflected back by an SMR at the point of inspection. When the beam re-enters the laser tracker it is converted into an electric signal, which is then analysed to determine it's time of flight (FARO, 2009). The time of flight is calculated by a method called phase modulated distance measurement. This methodology is best described in the NGCW SoA Report #8 (Airbus and Bath, 2010):

"This technique compares the phase of a reference signal with that of a measurement signal. It is similar to IFM with the fundamental difference that a modulated signal is used rather than the waveform of the light itself. This allows the frequency (and therefore the wavelength) to be adjusted until the reference signal and the measurement signal are in phase. The frequency is then increased until the next point where both signals are in phase. It is therefore possible to determine the absolute distance to a target by finding two successive frequencies which both match the phase of the reference signal." The equation used to calculate the distance is the following:

$$d = \frac{c}{2(f_2 - f_1)} \qquad (4)$$

Where d is the distance to be measured, c is the speed of light, and f_1 , f_2 are the respective frequencies.

ii) Coherent Laser Radar (CLR)

CLR is commonly known as "Laser Radar" and is also an ADM technology that works in a similar way to the technologies previously described. The main difference between these systems and CLR is that Laser Radar detects and uses diffuse light that has been reflected by the object being measured. This means that CLR does not require an SMR or any other type of retro-reflective target to send the laser beam back to be able to take distance measurements. From the reflection, it can determine the position of the object and thus perform a much quicker analysis on the object and several points at the same time. This results in a point cloud, which with the use of software enables a 3D model of the part to be built on which all the analysis can be performed instead of individual points that are obtained from the laser trackers or FSI. The time savings with this technology are considerable. A measurement of 100 points with a single ADM laser tracker is likely to take approximately 30 minutes to complete, while the same measurement performed by a Laser Radar will only take approximately 3 minutes (Airbus and Bath, 2010).

Currently, the capabilities of a CLR include a scanning speed of up to 2000 points per second and an accuracy of 10 ϻm + 2.5µm/m (Nikon, 2017). This accuracy was obtained by the manufacturer in a lab, under controlled conditions and, to enhance the CLRs accuracy the measurements are taken as close as possible to the target, with tooling balls on the objects to get better reflections, and less uncertainty. This is the equivalent of using SMRs, which to some extent defeats the purpose of the CLR. However, even when the tooling balls have been removed the instruments accuracy is still comparable with large CMMs and photogrammetry. As such, the CLR has been used by Airbus in an automated inspection process for the A340/350/380 composite nose cowl in which an increase of 60% in productivity compared with the previous inspection process was achieved (Nikon Metrology, 2017). The main disadvantage of CLR is its price. A CLR is approximately £350,000, compared to a laser tracker that is approximately £175,000 for the most equipped version the price difference and lack of accuracy most of the times does not justify its use instead of an SMR coupled with a laser tracker. However, CLRs are mainly used where the measurement volumes are in the high end spectrum of LVM. Examples of these include measurements of buildings, wind turbine blades, mirrors for space telescopes, and parabolic communications antennas (Nikon Corporation, 2017).

2.4.2 Photogrammetry

The term Photogrammetry is derived as follows (Walford, 2007):

- **'Photo':** Light
- **'gram':** Drawing
- **'metry':** Measurement.

In other words, due to the light that is coming from an object going through the camera's lens an image or "drawing" is formed in the camera's sensor. Then, with the help of software, the user is able to "measure" or create a 3D profile of the object being observed. Figure 10 illustrates the infinite possibilities for point of origin of a ray of light detected by the camera. It shows that the point can be anywhere on the ray.

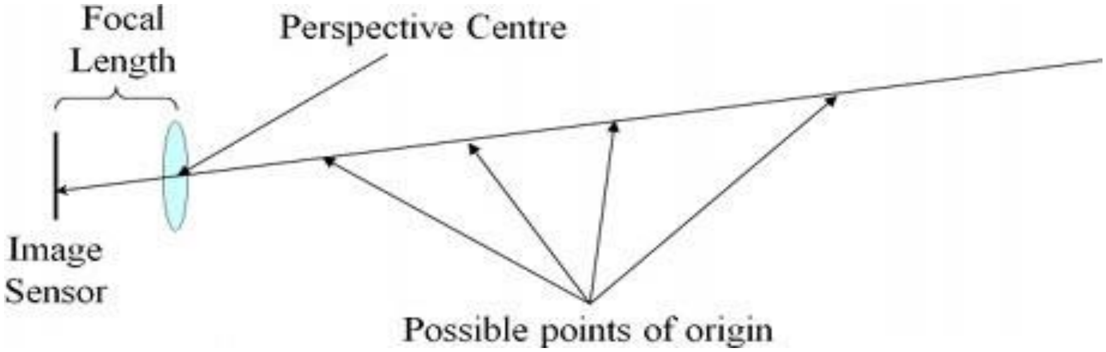


Figure 10- Possible points of origin on a single array of light (ADAM Technology, 2017)

When a picture is taken it is effectively being converted from a 3D representation into a 2D image, with a loss of information during the conversion. This information is depth (as can be seen in the figure above the point of origin is unknown). In order to be able to create a 3D profile, or to conduct a measurement and regain this information, a second picture of the same object needs to be taken from a different angle and position. Once at least two pictures of the same object are taken from different positions, it is possible to mathematically process this information to regain the depth, position and distance that was lost when the picture was taken. The triangulation method can be seen in Figure 11 where two pictures from different locations are taken enabling the depth, distance, and position of the object to be determined.

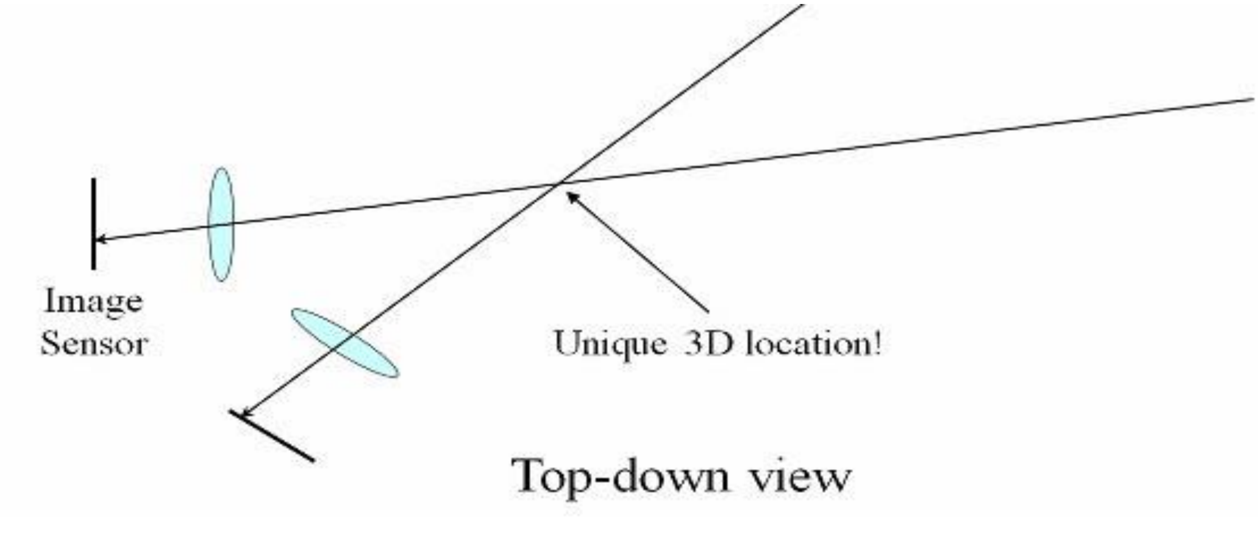


Figure 11- Diagram of triangulation (ADAM Technology, 2017)

Once the information has been processed and the correct scale is present in the picture, it is possible to conduct precise scientific measurements and verifications on the object being inspected, without the need of contact with the component. If applied correctly, photogrammetric methods can be an effective non-invasive verification system.

2.4.3 Metrology Software

This section will review the current metrology software used in LVM. Currently, the majority of metrology hardware manufacturers create their own software to complement their respective equipment. However, dedicated software can be limited in capability, reducing the number of available tools to the user. Also, integrating measurements from disparate measurement technologies (perhaps from different suppliers) is often difficult if not impossible. Due to this, there is another set of metrology software which is created by third-party companies which can accommodate more system interfaces, and provide a broader set of tools that can be used for the post-processing of the data. These software tend to be a 3D environment in which a metrology system comprising different types of instruments from different manufacturers can be based, and a full inspection process can be performed.

Some of the most commonly used third-party metrology software are:

- SpatialAnalyzer (Kinematics, 2017)
- BuildIT (BuildIT, 2017)
- Metrolog (Metrolog, 2017)
- Verisurf (Verisurf, 2017)
- Polyworks (Innovmetric, 2017)
- Geomagic (Geomagic, 2016)

An in-depth explanation of each of these software packages will not be provided, as each package contains an extensive set of tools and applications in which they can be used. However, the main difference between these software packages tend to lie in which area of metrology the software will be used, and personal preference for the graphical interface and set of tools available. For example, Geomagic and Polyworks tend to be software that focuses more on scanning and reverse engineering. Whereas, SpatialAnalyzer and BuildIT have been developed specifically for LVM applications. The following is a list of tasks that can be done by these third-party software:

- Comparison of components or assemblies to CAD.
- A 3D environment where different metrology equipment from different vendors can be used and integrated to perform an analysis of the data collect from the inspection process. This is typically termed, bundle or network adjustment.
- Reverse Engineering.
- Uncertainty Analysis.
- Scripting. This refers to the ability of the software to create custom “scripts” that can automate or semi-automate a measurement process.

Figure 12 is an example of inspection performed in SpatialAnalyzer on a component which is being compared to its CAD model, and where the deviations can be seen by the coloured spikes.

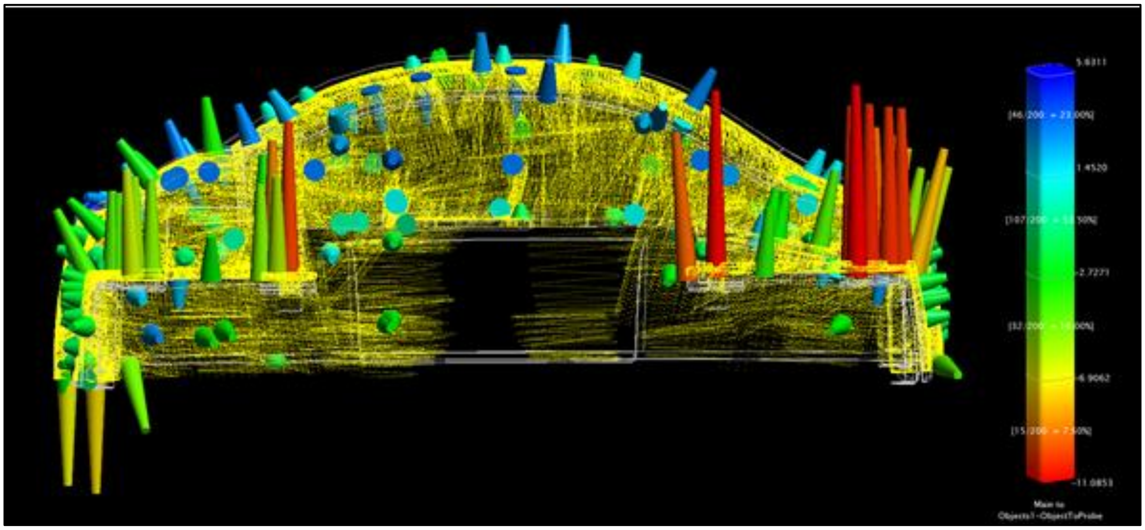


Figure 12 - Example of a comparison to CAD in SpatialAnalyzer.

2.5 Large Volume Metrology (LVM)

Large Volume Metrology (LVM) is the measurement of the size, location, orientation and shape of large objects such as car, plane, and ship parts (EURAMET, 2017). Due to the size of these assemblies, they are often too large to transport to a specialised laboratory to be measured. Hence, metrology equipment is brought to the assembly lines to perform the required inspections. The most commonly used tools in LVM are the laser tracker, photogrammetry systems, and scanners (Muelaner and Maropoulos, 2014).

In order for the assemblies being built in high value industries (i.e. aerospace, energy, and healthcare) to perform correctly, control of the position and dimensions of key components at the tens of micrometres level has to be performed within large volumes (LUMINAR and EURAMET, 2016). The instruments used in LVM are all optical measurement technologies. This means that the transfer of information between the measurement instrumentation and the measured object is achieved via light rays propagating in the atmosphere. Due to measurements being performed in the factory, these are not conducted in vacuum, but in air. Thus, the first order approximation in which light rays are assumed to travel in a straight line and a constant speed is no longer valid (Estler *et al.*, 2002). This is due to the changes of the refractive index in the air affected by the changes in temperature and humidity in the environment. This introduces one of the main challenges in LVM; measurements are performed in large buildings with complex temperature distributions, resulting in several complications. One of these is the bending of rays of light due to refraction, caused by temperature gradients in the environment. The following are two examples of apparent target shifts due to ray bending caused by refraction (Robson *et al.*, 2016):

- **0.5 °C per meter:** Over a 10m horizontal range, deflection is 50μm. Over a 30m horizontal range, deflection is 0.4mm.
- **1.5 °C per meter:** Over a 15m horizontal range and 6m height difference, deflection is 0.175mm.

The compensation of the index of refraction is considered by some as the biggest obstacle in large scale optical metrology today (Meiners-Hagen *et al.*, 2016).

One of the possible solutions to minimize the impact of the changes in the refractive index is a low cost, remotely-accessible, digital, open source logging and alerting system that provides on-demand determination of group refractive index and logs raw environmental data (Lewis, Campbell and Stavroulakis, 2016). This environmental monitor could be used to log the temperature of multiple locations to be able to derive 3D refractive index in large environments, where technologies such as laser trackers, could benefit from higher spatial resolution refractive index data.

Another of the complications is due to variations in temperature is the thermal expansion or contraction of materials. In many cases, the largest source of measurement uncertainty is thermal expansion (University of Bath and LUMINAR EMRP Project, 2016). A proposed solution for this problem is a “hybrid approach” proposed by Yang et al. (Yang *et al.*, 2017) in which the nominal and measured geometry are handled together. In this study, they use finite element analysis as an improved means for undertaking thermal compensation. They state that a “good” agreement was achieved between the analysis results and those obtained by measurements. Furthermore, this agreement was significantly better than that achieved through linear scaling with the coefficient of thermal expansion of materials.

Accurate measurements in LVM are important as better accuracy reduces the amount of excess material required, enables more complex designs to be achieved (LUMINAR and EURAMET, 2016). This will inevitably result in cost savings and more efficient assembly processes.

2.6 Augmented and Mixed Reality

This section will explain AR, how it works, its current implementations in manufacturing and assembly, and how this technology has been used in the area of measurement and verification processes. Furthermore, state-of-the-art technology in MR will also be presented and explained.

AR can be described as a human-computer interaction that blends the natural view that the user has of reality with digital information that can be of use in that location and at that time. This digital information can be anything from videos, images, and text. What gets displayed will depend on the environment and current situation the user is in. This digital content has the capability of enhancing or “augmenting” the reality that the user is experiencing. It is important to mention that contrary to Virtual Reality (VR) where the real world is blocked and what the user sees is a virtual scene, AR is achieved without the user losing sight of the real world. This is the main reason why AR can be used for context-specific tasks, and has the potential to help in training, design, assembly, and verification and validation processes (Radkowski, Herrema and Oliver, 2015).

An AR system has four key components (Daponte *et al.*, 2013):

- Video camera
- Tracking module
- Graphic Processing Unit (GPU)
- Display

The video camera captures the real-world environment that the user is currently observing. Then the tracking module is in charge of calculating in real time the actual position and orientation of the camera. The tracking module is considered to be the most important component of an AR system (Daponte *et al.*, 2013) since without knowing the location of the camera or where the user is, the AR system does not know where to place the digital content. After the tracking module has successfully obtained the location and detected the markers, the GPU, with this information now knows what it needs to display and where it needs to be displayed. It creates the digital information and passes it along to the display in order for the user to be able to observe it. There are different type of AR displays. These are hand-held displays (smartphones, and tablets), monitors, projectors, and Head Mounted Displays (HMD).

Since the tracking module is an important component of the AR system, a more in depth explanation on how it works will follow. AR systems can be classified into three categories depending of which type of tracking system they use (Krevelen and Poelman, 2010). These three categories are:

- Marker and Marker-less vision based systems
- Sensor based systems
- Hybrid tracking system

There are two types of marker based AR systems. The first is an ID-encoded marker which is normally referred to as a “marker based AR system”. These markers will each have a unique pattern on them and when the tracking module detects them, it can calculate its position, while the GPU finds the corresponding digital content for that pattern and then overlays it on top of that marker in the display. These markers are normally used when the application at hand has a considerable number of markers to be matched. The advantages of these type of systems is that a marker based AR system can be more accurate than a marker-less system providing less jitter, demands less performance requirements from the system which results in a quicker marker recognition. However, the disadvantages of this type of system is that a unique fiducial marker is needed for each augmentation. Which means that this can be considered an invasive system as markers will need to be placed throughout the environment that is being augmented. Time will also be required to set up and calibrate the markers (Tiefenbacher, Lehment and Rigoll, 2014) & (Daponte *et al.*, 2013).

A marker-less AR system works on the basis that the tracking module will detect key features of a specific image, object or template, and calculate the position of the marker with those key features. According to (Daponte *et al.*, 2013) these key points must have the following characteristics:

- They should be able to be recognised as fast as possible.
- They should not present much variation under varying lighting conditions or in case the image can be blurred.
- They should hold under different viewing angles
- The object, image or template being used should have enough key features to be able to be tracked through a range of distances between the user and the object in question.

The more key features from the object that resemble the characteristics from the previous list, the better the marker will be. This often means that less performance is required and less jitter is present, which results in a quicker tracking and overlay of the desired augmentations. One of the biggest advantages of a marker–less system is as it name implies, there is no need for unique and ID-encoded targets to be placed in the environment or on the component to be inspected. Instead, key features from the objects and environment can be used as “markers” to calculate the position and overlay the augmentations, accordingly. Consequently, this would no longer be considered an invasive system.

The techniques implemented for AR sensor-based systems are considered to be fast and robust and can be used for motion prediction. However, these systems are regarded as being less accurate than a vision based system (Lang *et al.*, 2002). The sensors normally used for these tracking techniques include sensors such as GPS, ultrasonic sensors, optical sensors, a pulsed infrared laser diode, and inertial sensors (Rolland, Baillot and Goon, 2001). Almost all of the previous tracking sensors that have been mentioned calculate their position by triangulation. According to Aron et al. (2007) inertial sensors are the most popular due to their high frequency response and their robustness in different light conditions; however, they do have low accuracy.

The major challenge for tracking modules in both marker and marker-less AR systems is that the processing time required by the GPU is longer than with sensor-based AR systems, which can result in time lags in the augmentations. Another challenge is that misalignments can occur during the overlay of the desired virtual content due to a mismatch of markers or key features (Daponte *et al.*, 2013). Regarding a sensor-based AR systems, their main challenge is low accuracy, which can result in misalignments of the digital content. As can be observed, regardless of the system used as a tracking module, it can still be affected by misalignments. This is an important challenge to overcome as misalignments of the digital content with respect to the real world can cause confusion, disorientation, and misinterpretation of instructions that can result in user errors.

One attempt to overcome these challenges utilised a hybrid tracking AR system (Aron, Simon and Berger, 2007). This system used a combination of a marker/marker-less systems and a sensor-based system. This creates a more robust tracking system. Since there are occasions where a vision-based system cannot fully provide the locations needed, the sensors can provide extra support to accurately calculate the positions needed or vice-versa when the sensors cannot provide the locations themselves (Daponte *et al.*, 2013). Such a system was proposed by (Aron, Simon and Berger, 2007) where they used a combination of a vision-based system with inertial sensors for their tracking module.

i) Mixed Reality Hardware

Several companies have announced new MR headsets. However, the Microsoft HoloLens (Microsoft Hololens, 2017) is the only commercially available MR headset at the time of writing of this thesis. The only other alternative to the HoloLens is an in-house creation of a MR headset. These two types of technologies are described below.

The HoloLens is the first self-contained, untethered holographic computer that can be bought on the market. Although it is still in development, the HoloLens enables users to interact in real time with the digital content that is overlaid in the real world. This content is in the form of holograms, and these holograms are interacting with the user and the real world simultaneously. The user can interact with the holograms through voice commands, hand gestures, and gaze tracking. The HoloLens consists of the following hardware:

- **Sensors:** Inertial Measurement Unit (IMU), 4 environmental understanding cameras, a mixed reality capture sensor, 4 microphones, and an ambient light sensor.
- **Processor:** A custom built Holographic Processing Unit (HPU), and an Intel 32-bit architecture.
- **RAM:** 2 GB
- **Camera:** 2MP photographic camera, and HD video.
- **Connectivity:** Wi-Fi 802.11ac, Bluetooth 4.1 LE, and a Micros-USB 2.0 connection.
- **Power:** 2-3 hour active battery use.
- **Operating System:** Windows 10 with a Human understanding of spatial sound, gaze tracking, gesture input, and voice support.

In addition to being able to see 3D holographic representations on the real world of designs, prototypes, and models, the HoloLens allows teams to be able to collaborate on the same hologram regardless of whether they are in the same location. Furthermore, if the users are in separate locations, the technology allows both users to see what the other person is seeing, thus enabling one user to guide the other through a process or simply interact with the world that the other is seeing. This feature has the potential to make remote collaborations easier, more efficient, and far more interactive (Microsoft Commercial, 2017)

Currently, the HoloLens is being used in the health, construction, design, education, manufacturing, and entertainment industries to train employees, reduce prototype times, collaborate, educate, and communicate more efficiently (Microsoft Commercial, 2017). Figure 13 presents an image of the HoloLens headset.

Figure 13 - Microsoft HoloLens headset (Microsoft Hololens, 2017).

An in-house made MR headset could be achieved by using a VR headset and mounting on it a camera that would capture the real environment and blend it with the digital content being fed to the VR headset in order to obtain a “mixture” of the two realities (Syberfeldt et al., 2015). Figure 14 shows the headset, which comprised an Oculus Rift VR headset and two cameras mounted in front of it. The disadvantage of this type of headset is that it isolates the user from the real world, which is not ideal in an industrial environment due to health and safety concerns. Furthermore, these headsets do not have the same number of sensors and hardware set-up as the HoloLens, which limits the flexibility, dynamics, and adaptability of the digital augmentations to interact with changes in the environment or actions from the user.

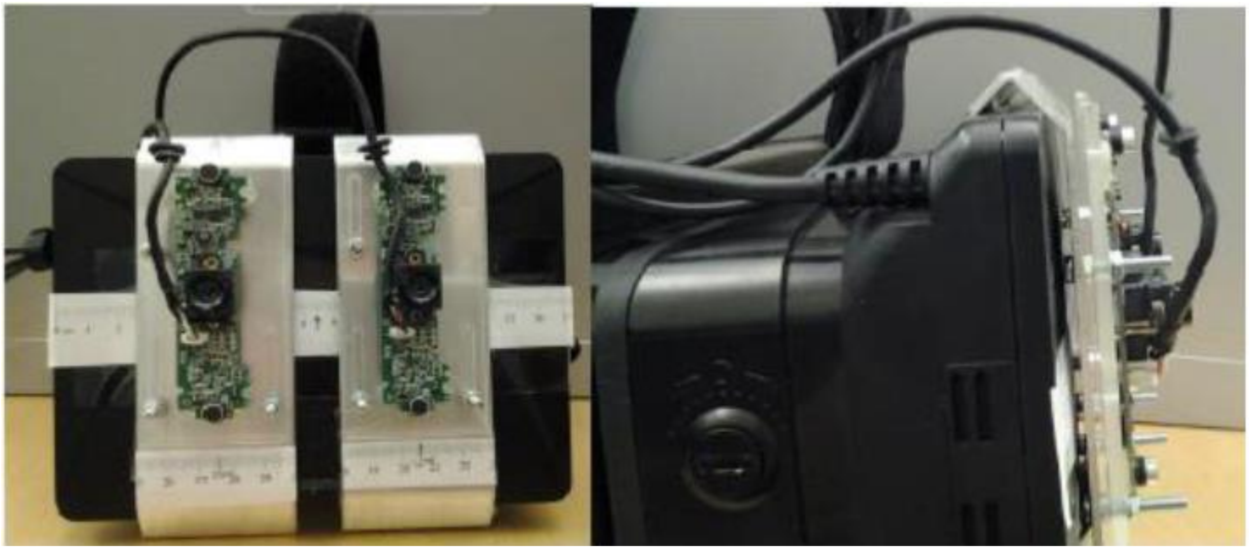


Figure 14 - In-house built headset used by Syberfeldt et al. (2015) *in their research*

2.6.1 Implementations of AR in the Industry

Since its inception in the 1960's (Augment, 2016), Augmented Reality has been used for several applications that include the entertainment industry, marketing campaigns, and the industrial sector to aid engineers and operators in the training, design phases, and assembly guidance. According to (Wang, Ong and Nee, 2016), AR's ability to improve the interaction between the computer systems and users, permit them to move freely in an augmented environment. This allows the user to interact with digital objects naturally. Hence, AR technology has been positioned as one of the most promising technologies for assisting in assembly processes.

In 2016, Wang et al. (2016) conducted an in-depth survey of the research carried out in AR for assembly. They analysed every paper that was published from 1990 to 2015 that discussed AR for assembly, leading to 304 papers being selected and organised in to three main categories and twelve sub-categories. Figure 15 shows the number of papers over time for each category and sub-category.

As can be seen from Figure 15, the category with the most publications and research performed in the area is AR assembly guidance with 120 articles, followed by AR assembly design, simulation, and planning with 116 articles, and lastly AR assembly training with 68 papers. The category of AR assembly guidance and its subcategories will be further analysed.

As seen in Figure 15, AR Assembly guidance can be broken down into six sub-categories:

- Interactive instructions
- Multi-media instructions
- Context-awareness
- Authoring
- Effectiveness evaluation of AR assembly systems
- Usability evaluation of AR assembly systems.

The following is an overview of previous work conducted in the areas of interactive and multi-media AR assembly guidance, context-aware AR systems, effectiveness and usability evaluation of AR systems.

Year	AR assembly guidance						AR assembly training			AR assembly design, simulation & planning					Total
	Interactive instructions	Multi-media instructions	Context-awareness	Authoring	Effectiveness evaluation	Usability evaluation	Procedural tasks	Design guidelines	Feedback	HCI (tool based)	HCI (glove based)	HCI (hand based)	Assembly simulation	Assembly design and planning	
2000	3	7	1	1	2	1	3	0	0	4	0	0	0	1	23
2001	0	2	1	0	0	0	0	0	1	0	0	0	0	0	4
2002	0	1	1	1	0	1	1	0	0	0	0	0	0	0	5
2003	1	3	1	1	2	0	2	0	0	2	0	0	0	2	14
2004	1	2	1	2	1	1	2	0	0	2	0	0	0	1	13
2005	1	1	1	0	1	1	1	0	1	1	1	0	2	2	13
2006	0	0	0	0	0	0	0	0	0	1	0	0	1	1	3
2007	1	1	0	0	0	0	0	0	1	2	0	1	1	1	8
2008	2	2	1	0	4	1	2	0	1	4	0	0	3	3	23
2009	2	3	0	0	1	2	4	0	2	6	1	1	5	5	32
2010	1	1	1	2	1	1	2	2	2	3	0	1	3	4	24
2011	5	0	3	0	5	1	4	6	7	4	1	3	7	4	50
2012	1	0	3	3	0	0	2	0	3	5	0	1	1	3	22
2013	2	2	4	2	5	1	3	1	8	3	0	3	4	3	41
2014	4	1	3	2	2	1	4	0	3	1	2	2	1	3	29
∑	24	26	21	14	24	11	30	9	29	38	5	12	28	33	304
%	7.89	8.55	6.91	4.61	7.89	3.62	9.87	2.96	9.54	12.5	1.64	3.95	9.21	10.9	100

Figure 15 - AR assembly research in the literature (Wang et al. 2016)

i. Interactive and Multi-media AR Instructions

In 2003, Tang et al. (2003) did a comparative study between three different types of guided assembly methods. The first one was a paper-based manual instruction set, the second was a Computer Assisted Instruction (CAI) method using a monitor as a display, and the third used an AR HMD to overlay the assembly instructions over the workspace. The results showed that using the AR system reduced the error rate for an assembly task by 82%, in particular cumulative errors. The results also showed through a measurement of the mental effort during the assembly that the mental workload was reduced with the AR system.

In 2003, Wiedenmaier et al. (2003) after comparing an expert guided assembly, an AR guided assembly, and a paper based assembly found that an assembly was completed in the shortest amount of time when an operator was guided by an expert, the second shortest completion time was an AR guided assembly, and in last place came a paper based guided assembly. Hou et al. (2013) conducted an experimental study with 50 participants to test the potential cognitive gains of an AR assisted assembly system in comparison with a paper based instruction assembly. The findings showed that the AR system produced shorter completion times, less assembly errors, and lower total task load.

Xuyue et al. (2015) created a mixed reality scene that displayed instructions to aid a technician through an assembly operation, resulting in an improvement of the efficiency of the manual operation, and a better user experience when compared with traditional training methods. Zhu et al. (2014) created a guided assembly system that consisted of an AR HMD, and a virtual personal assistant. This system would provide an operator with visual, audio and locational cues. This system was used by a novice mechanic to successfully perform an advanced 33-step maintenance task on a military training vehicle.

In 2015, Syberfeldt et al. (2015) after comparing an AR guided assembly system with a paper based assembly method found that all six participants in the study managed to complete the assembly without any errors, while two out of the six participants using the paper instructions did make assembly errors during the trial.

In 2016, Makris et al. (2016) used an AR tool to develop a system to help operators to be in a hybrid human-robot collaborative industrial environment. This system was applied in an automotive case study demonstrating that the AR tool did help the operator feel more secure enhancing the operator’s integration with the assembly process.

ii. Context-aware AR systems

A context-aware AR assembly guidance system differs from the above systems as it will provide the necessary multimedia instructions based on the stage of assembly or step that the operator is currently in. This means that these systems will generally have a real-time feedback system in place that will evaluate the current assembly and display the corresponding information. The following are examples of systems found in the literature.

In 2003 the German Ministry of Education and Research funded the ARVIKA (Friedrich and Friedrich, 2002) project to develop and implement AR technology in the areas of development, assembly, and service for the automotive and aerospace industries. In order to achieve this they focused on the recognition of specific objects, attaching necessary information to these objects to deliver pertinent information according to the working context of the operator, and finally to design a user interface based on different interaction methods between the operators and the AR system.

Vignais et al. (2013) developed a system that detects the body position of the operator during assembly with position sensors. If the operator is in a position that could potentially cause an injury the system provides immediate visual feedback through a HMD as well as specific audio cues making the operator change position and thus prevent potential injuries. Radkowski et al. (2015) developed an AR system for a major manufacturer of electrical components in which they would detect the corresponding circuit board and, based on the type of circuit board, the AR system would display the necessary 3D models, 2D texts, and annotations to guide the operators through the assembly. Rentzos et al. (2013) designed an algorithm enabling an AR system to detect specific components of an automotive assembly and, based on these components, the system automatically generates the necessary instructions for the operator to complete the assembly. This way, it ensures a correct synchronization between the visual cues presented and the current state of the assembly.

Minh et al. (2014) were able to successfully trial two different methods of displaying information in an AR system to aid with an assembly of LEGO. However, as they trialled these two display methods the system would analyse the current state of the assembly and give feedback to the user if the component was incorrectly assembled. Thus, they managed not only to provide guidance through the assembly, but also include error detection information as well.

Erkoyuncu et al. (2017) developed a context aware adaptive authoring system to assist in maintenance operations called ARAUM (Augmented Reality Authoring for Maintenance). The main objective of this system was to support industrial maintenance operations by generating AR content that can guide an operator in real time. A participant based study with 8 participants was conducted in which ARAUM was compared against a real-life, complex maintenance manual. Half of the participants used the paper manual while the other half used the ARAUM system to conduct a maintenance task on a gear box. The results showed that the participants who used the ARAUM system completed the same maintenance task in half the time as their counterparts using the paper manual. Thus, it was concluded that AR can create opportunities for industrial maintenance applications through the displaying of contextualised information.

iii. Effectiveness and Usability Evaluation of an AR System

After more than 10 years of AR development there is still no clear standard on how to evaluate AR assembly systems, making it difficult to define the advantages of AR without well-defined goals and objectives of current procedures for an AR assembly task (Wang, Ong and Nee, 2016). The following are examples of how this has motivated several researchers to find different ways to evaluate an AR system.

Hou et al. (2013) stipulated that the evaluation of an AR system can be divided into two categories: effectiveness evaluation and usability evaluation. Effectiveness evaluation looks at the ability of a system to achieve a certain result for a specified task. These results can be the reduction of assembly time, assembly errors, improvement of assembly efficiency, etc. Usability evaluation on the other hand analyses the interaction between the user and the AR system, i.e. how user friendly or how easy the AR system is to use for the operators. This is normally evaluated based on user interviews completed once the assembly task has been performed (Wang, Ong and Nee, 2016).

In 2010 Stork and Schubö (2010) presented a study on the performance of human cognition in production environments, analysed through different theories from cognitive psychology. They tested these theories by observing how participants assembled a component, comparing three different type of information display. Two were different types of AR projector based displays and the third was a normal monitor instruction based display of instructions. The methodology presented by the authors aimed to prove how it is that the analysis of human information processes and psychological experiments can improve the evaluation of engineering applications.

In 2011 Henderson and Feiner (2011) created an AR guidance system that helped military mechanics perform 18 common tasks inside an armoured vehicle turret. They evaluated this prototype with a user case study that compared the AR system against a monitor display system. To evaluate the effectiveness of the prototype the following variables were analysed across the participants:

- Completion time.
- Task localization time.
- Number of errors performed throughout the maintenance tasks.
- Analysis of head movement through the procedure
- Mechanic's ability to stayed focused on a particular task

These variables were statistically evaluated for each display type by the calculation of the analysis of variance (ANOVA). For usability evaluation purposes, the participants were asked to complete a post-experiment questionnaire that evaluated the ease of use, satisfaction level, and intuitiveness for each display condition.

As mentioned in Section i, Hou et al. (2013) conducted two experiments with 50 participants in which they compared an animated AR system against a paper based manual system. One experiment measured the cognitive workload of using the two types of systems, and the other experiment measured the learning curves of novice operators. In order to evaluate the effectiveness of the system completion time, number of errors, and cognitive workload for each participant were monitored throughout the experiments. These variables were statistically analysed by the calculation of an ANOVA. To evaluate the usability of the system a post-experiment questionnaire was completed by each participant that assessed the input mechanism, visual output, disorientation, field of view, comfort, level of immersion, and different questions that evaluated the instructions of the different display systems.

In 2014 Odenthal et al. (2014) carried out two laboratory experiments in which 48 participants were evaluated while using either an AR system or a table-mounted display system to detect assembly errors on a Lego model. To evaluate the effectiveness of the system, each participant conducted eight trials while being evaluated on how long it took to detect the assembly error and the quality of the error detection (i.e. frequency of correctly detecting and identifying an error, frequency of incorrectly detecting an error, and frequency of not detecting an error at all). In order to compare these variables between display types, an ANOVA was performed. For usability purposes, a post-experiment questionnaire was applied to measure the level of visual fatigue of the participant.

Gavish et al. (2013) evaluated the efficiency and effectiveness of VR and AR systems for industrial maintenance and assembly training tasks against traditional training methods. 40 expert technicians were separated in 4 groups (VR, Control-VR, AR, Control-AR), given training, and then asked to complete a post-training test that evaluated performance on the real task. Means and standard deviations were calculated for training time, test completion time, number of solved errors, number of unsolved errors, and number of aids used during the test. Following the test completion, the technicians were asked to answer two questionnaires. The first questionnaire consisted of 5 questions that evaluated the transfer of learning that the systems provided. The second questionnaire had 9 questions that focused on evaluating the usability of the training platforms.

Radkowski et al. (2015) conducted a study with 33 participants that aimed to prove that in order to be able to obtain an advantage from an AR assembly guidance system, the visual features used to explain each step of the process must be equivalent to that step's difficulty level. In order to achieve this, a comparison was made between an AR system, and a paper based guidance system. For the AR system the type of visual features displayed changed depending on the task difficulty level. The augmentations varied in content by combining the inclusion or exclusion of text, 3D arrows, 2D schemas, 3D models, and animations to provide assembly information. The variables recorded throughout the case study were completion time and number of errors. In order to evaluate the hypotheses presented in the study a *t* test and an ANOVA were applied. According to their results the study concluded that using an AR setup that includes 3D models, text, and animations is better than simply using 3D arrows, 2D schemas, and just text. They also concluded that the use of AR "significantly" increased the user's confidence when performing the assembly.

Focusing on the usability of AR assembly guidance systems, Gattullo et al. (2015) conducted a set of experiments to investigate text style, colour coding, and lighting used in the user interface and the impact it has on the user experience. This was done with the intention of providing a guideline for designers of AR interfaces to use when designing the AR system. Each variable was tested in separate studies and then evaluated using ANOVA. As a result of this a guideline on text style, colour, and background configurations that can best be detected by the users of an AR setup are presented.

Palmarini et al. (2017), in the area of maintenance, presented a new process that can assist non-expert users to decide whether or not AR is a suitable solution for their application. If it is suitable, it helps streamline what hardware, development platform, and visualization method should be selected for that specific maintenance task. Although this process has not yet been validated, it presents the users with an in-depth guideline that can assist them in making the correct decision on whether or not to use AR, and which hardware and software to select without possessing expert knowledge.

iv. Augmented Reality for Measurement Applications

To the best of the author's knowledge, the following are the only applications in which AR has been used to purposefully aid with verification and validation in the manufacturing or assembly of a part that is used directly in an industrial application.

In 2010 Yamauchi et al. (2010) successfully trialed a system composed of an optical shape measurement instrument and an AR HMD display system for a line heating task performed as part of the shipbuilding process. The system measured the deformation of the plate and projected these results in a form of a line through the HMD for the operator to follow with a heating instrument in order to bend the plate in to the desired shape.

Since 2013, FARO have partnered with Metaio (an AR company that now has been bought by Apple (Miller, 2015)) to create a workstation that allows the FARO hardware (measurement arms) to help the AR software perform highly accurate tracking that enables the AR system to accurately overlay CAD information on to a real component seen through a tablet or HMD. This allows quick visual comparisons, assembly checks, assistance in error identification and deviation checks (FARO, 2015). The original company that provided the AR capability (Metaio) is no longer operational. However, they have recently made an acquisition of a mobile AR German company, MWF Technology (MWF Technology, 2017). MWF's technology enables large, complex 3D CAD data to be transferred to a tablet device and then used for mobile visualization and comparison to real world conditions.

- 8-tree's structured light scanners

8-tree has developed three very specific structured light scanners. These are for applications to check and verify gaps, dents, and fasteners (for aircrafts). 8-tree focused on a specific problem, simplifying constraints in order to make a quicker, simpler and easier to use technology with the combination of AR and the principles of usability engineering. Their result is a product that can, in a matter of minutes, display on the surface of the object being inspected if the feature is placed correctly and, if it is inside its tolerance zone. This allows the operator to make rapid decisions if the part is a go or no-go. Below pictures of this technology are presented.

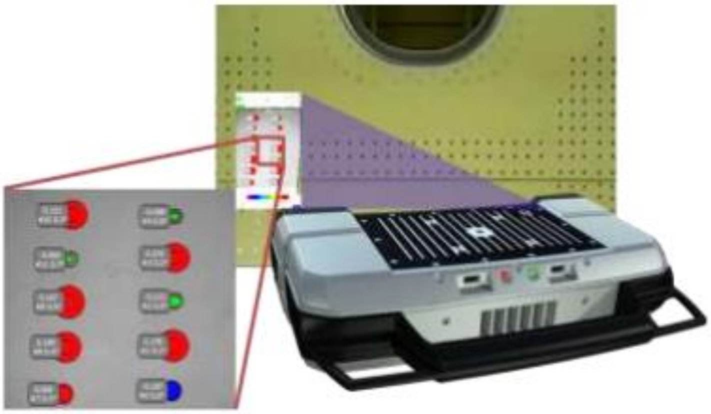


Figure 16- The fastCHECK system (Klaas, Chhabra and Bottcher, 2013)

Figure 17- The gapCHECK system. (Klaas, Chhabra and Bottcher, 2013)

These scanners are used for rapid verification on three specific areas which are dent checks, gap checks, and fastener flush check. 8-tree is using AR in their technology to achieve three main goals (8tree, 2017):

- To not use a computer monitor.
- To provide immediate feedback on the component itself.
- To create a visual link between the component and the inspection results that is easy to understand and can quickly be acted upon.

The paper that includes the full explanation of what these tools do, and the philosophies behind it can be seen in reference (Klaas, Chhabra and Bottcher, 2013).

2.7 Critique of the Literature

The following is a critique of the literature which is the most relevant to this research.

i) Critique of Literature in Large Volume Metrology

- As expressed by the European Association of National Metrology Institutes, the LVM industry has several issues that need to be addressed. These issues are: refractive and thermal effects on optical tools; non-optimum procedures for instrument performance; a lack of sound metrological knowledge and poor understanding of the dynamic behaviour of LVM tools (EURAMET, 2012). In other words, design, production and inspection teams are uncertain as to what their current measurement capabilities are, which instruments to select, what the impacts of the environment on the measurement process are, what the inspection sequence should be, what are the best features to measure, and how is it that they can achieve the necessary traceability and conformance to the conditions of supply stipulated by their customers. It is important that members of each of the these teams are at least aware of these issues as this can result in an achievable inspection process that would enable a more streamlined assembly by reducing bottlenecks, and re-planning of assembly and inspection plans.

- Francis et al. (2016) have stated that there is a knowledge gap within design and manufacturing communities for large aerospace structures when it comes to assigning tolerances based upon estimated measurement uncertainty. The result of this gap is that metrologists are left with technical drawings and specifications that demand unachievable measurements over the specified volumes. This can be due to various factors, including: the metrology instruments, budget and environmental factors in the assembly lines. In order to solve this issue, they proposed a novel Design for Verification (DfV) framework. This framework assists designers of low rate, high value products with a guide that aims to optimise tolerancing, assembly, tooling and measurement. This framework was used in the aerospace industry and demonstrated improvements in tolerance analysis and synthesis, optimized large volume metrology and assembly process and more cost-effective tool and jig design when used in conjunction with other "Design for X" methods.

The DfV framework has been a valuable addition for design and manufacturing teams as it has shown noticeable improvements on tolerance setting, optimisation of metrology and assembly processes, as well as more efficient tools and jigs. However, there is still a gap in being able to transfer and implement this knowledge to the actual shop floor and guarantee that the operators understand what they need to be doing, whether they are doing it correctly, and that all processes are documented. In the majority of cases, inspection plans cannot be carried out by operators and in most cases must be carried out by trained metrologists, resulting in longer verification and assembly times.

ii) Critique of Literature for Augmented Reality

- Throughout the review of the literature it was noted that the majority of research on AR for assembly tested the designed AR systems with simple assembly tasks, the majority of which were performed with Lego. This was further highlighted in Wang et al’s. (2016) survey that analysed 304 papers that addressed AR for assembly. One of the conclusions stated that due to most of the case studies being simple assemblies, future work should focus on the capability of an AR system to provide assistance in a complex, multi-step assembly task. This should be taken into account during the design of the experimental tests for this research.

- Yamauchi et al’s. (2010) work is the closest the author found to a fully integrated measurement and AR system. The system measured the deformation of the plate and projected these results in a form of a line through the HMD in real-time for the operator to follow with a heating instrument in order to bend a metallic plate in to the desired shape. However, this system did not have control of the measurement hardware or software through the AR system. Both the AR and measurement systems were controlled separately. Furthermore, the user did not receive any information regarding the set-up of the system, its environment, if the equipment was ready to be used, and analysis of the finished part with respect to design specifications.

- Daponte et al. (2013) highlighted several problems that inhibit the implementation of a measurement system based on AR with two of these gaps being identified as crucial. 1) It is necessary to integrate the measurement instruments with an AR system. Neither this gap nor the obstacles of being able to integrate the metrology instruments with AR systems identified were discussed further in this paper. To the best of the author’s knowledge, this problem has not been addressed or solved in any other publicly available research. This issue should be addressed in this research at the time of the identification and selection of appropriate hardware. 2) Measurement data captured from the assembly inspection must be presented logically, simply, and intuitively to the user so that they are able to act quickly and correctly based on this information. Similar to the previous gap this paper did not mention how to address this issue nor what were the challenges encountered in order to present the information in the best way possible to the user. This issue is further discussed in the next point.

- Once data capture from the inspection process is completed, it is important to define how this information is used and presented to the operator. Currently, there are two companies who have done work in this area, 8tree (8tree, 2017) and Faro with its AR Inspect technology (FARO, 2015). Both technologies have been described in this chapter. These technologies present the information in a simple way that allows the operators to make comparisons, view results and make informed decisions based on the data presented. However, the 8tree technology can only be used on small sections of the assembly at a given time and it can only be used for three very specific verifications. These are the analysis of the flushness of fasteners, dent inspections, and analysis on the size of gaps on an aircraft's fuselage. Regarding the Faro AR inspect system, there is no current experimental data to provide accurate validations of its use and functionality in a real industrial environment. As mentioned in Section 2.6.1, MWF's technology enables large, complex 3D CAD data to be transferred to a tablet device and then used for mobile visualization and comparison to real world conditions. From the information available, FARO AR Inspect appears to be limited to tablets and screens, which either turns the user's attention away from the assembly or does not allow the user to operate hands free. According to Odenthal et al's. (Odenthal *et al.*, 2014) study, the display type significantly affects the frequency of error detection; correct error detection and identification are improved by 36% when using the HMD compared to the TMD. Furthermore, FARO AR Inspect does not offer any capabilities to aid with setting up of the instruments, creation of a reference network, nor environment monitoring. It is a system that is tailored for experienced users and relies on the assumption that the user has carried out the previous steps correctly.

2.8 Research Gaps

After the review and critique of the literature, the following gaps have been identified in the area of LVM and the use of AR for measurement:

i. Address refractive and thermal effects caused by the environment on LVM optical tools, and assemblies.
ii. Inspection processes suffer from non-optimum procedures for LVM instrument performance.
iii. There exists a lack of comprehension and implementation of the fundamentals and best practices of LVM, resulting in a poor understanding of the dynamic behaviour of LVM tools and inspection processes.
iv. The challenges that need to be overcome in order to fully incorporate metrology hardware and software with current AR and MR technologies have not yet been identified.

v. A methodology that allows the presentation of digital information through AR or MR technology in a way that it is easily understood by the user has not yet been identified.

vi. The development of hybrid tracking technologies, sensors, and display technologies that can reduce invasivity of AR and MR systems.

vii. The majority of AR assembly guidance systems focus on providing a step-by-step instruction, while failing to identify or provide a timely guidance of the instructions in the assembly process.

viii. Most of the case studies found in the literature were performed with simple assemblies. Therefore, future work should focus on the capability of an AR system to provide assistance in a complex, multi-step assembly task.

ix. Given that an AR interface could disturb or interrupt an ongoing assembly task, it is important to research the ability to detect and recognize the operator’s actions in order to provide a true industrial hands free system.

3. Scope of the Research

3.1 Introduction

The literature review in Chapter 2 concluded by critiquing and identifying nine research gaps in the areas of metrology, AR in assembly processes, and AR in verification and validation of components and assemblies. Based on the gaps identified, the novelty of this research is the combination of the following three ideas. The first idea is the combination of new MR technology with metrology hardware and software. The second idea is the full integration of the MR technology with the metrology equipment. This is, that it should be possible for the user to only interact with the MR device and from there control both the metrology instruments and software. This would then enable a true immersive system. The third idea is to compare the user performance when using the immersive system against current best practice. To the knowledge of the author, the combination of these three ideas is something that has not been achieved before. The reminder of this chapter outlines the research context, boundaries, and research questions that will be addressed. Finally, the research methodology will be defined.

3.2 Research Context and Boundaries

The context of this research is AR within verification and validation of large volume assemblies. This research does not develop new metrology or AR technologies. Instead, it studies the effect of the combination of the two technologies in user performance with respect to current best practices. Boundaries have been identified that focus on the key elements of metrology, AR, and verification and validation. These boundaries are illustrated in Figure 18 and are further explained below:

i) AR HMD: Currently there exists a wide range of display technologies. These include LCDs, tablets, mobile phones, VR headsets, projectors and diverse AR technologies. Within AR there is hand held technology, projected AR, and AR HMDs. This research focuses on AR HMDs for the implementation of the ISLVM.

ii) Verification and Validation with AR Technologies: As identified in the literature review, AR has been used for more than a decade on assisting operators through manufacturing and assembly processes, as well as being used as a training tool for specific maintenance and manufacturing activities. This research will not focus on assembly, manufacturing, or training guidance. Rather it will focus solely on the implementation of AR for verification and validation procedures.

iii) In-process Verification: Verification of assemblies can occur at different points in the process and in different locations. That is, assemblies could be inspected while on the assembly line, or once an assembly stage is completed it can be moved to a metrology area for inspection under certain conditions. There are also different inspection methods such as batch testing, or inspection of every component that have been assembled. This research will only focus on in-process verification. More specifically, the verification of components that are still on the assembly line and will not be moved to a metrology lab to be inspected.

iv) Digital Implementation of Key Metrology Concepts and Best Practices: Metrology is an important facet of engineering that enables correct parts and components to be manufactured to exacting and specified limits and specifications. Metrology methods consist of using specific technologies and standards that can assist in measuring increasingly complex engineering components. This research will not be developing new metrology hardware, nor standards. Rather, it will digitally implement key metrology concepts, procedures and best practices.

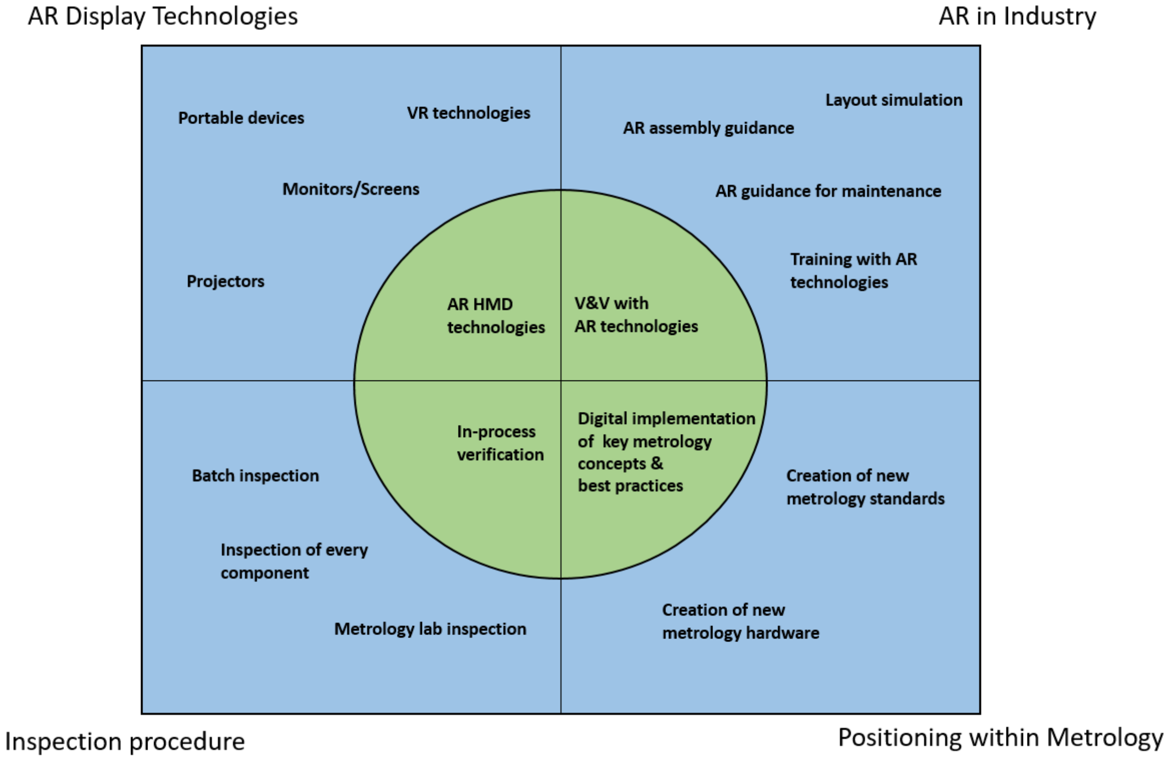


Figure 18- Research boundaries within the context

In addition to the context and boundaries detailed in Figure 18, two further research boundaries have been identified. The first of these boundaries addresses environmental conditions within the measurement environment which have not been considered. Hence, efforts to control, measure, or compensate for environmental effects (such as changes in humidity and temperature, or vibrations) are outside the scope of this research. The second of these boundaries further details the scope of this investigation by monitoring users as they conduct measurements. As such, preliminary activities such as setting-up the metrology hardware, setting-up of a reference network on the actual component will either be supervised or completed before the experiment commences. Furthermore, projecting the measurement results on to the assembly is a downstream process, and is not considered in this research. It is important to state that this investigation considers a single operator performing the inspection process. The reason being that it is envisioned that the ISLVM will eventually be used in a measurement-assisted assembly process, where a sole operator performs assembly and inspection simultaneously.

3.3 Research Questions

Based on the gaps identified in the literature review in chapter 2, and the aims, objectives and scope previously defined, a set of questions that this research will address have been defined. These questions reflect current theory within the areas of metrology, and AR in verification and validation. These questions will be used in chapter 5 to deduce the hypothesis that will be tested in the experimental process. The questions are as follows:

Q1. Can the use of modern AR technology enable a single operator performing an inspection task to commit less errors than the current tools used in a verification process?

Q2. Can an operator wearing an AR HMD successfully complete an inspection process?

Q3. Can modern MR technologies integrate seamlessly with current metrology hardware and software in order to be used in an inspection process?

Q4. Will the comfort of the MR HMD, the physical and mental load generated from the device usage, and how the information is presented to the user through the device have a direct impact on whether the operator prefers to use the ISLVM over current inspection methods?

Based on the findings from the literature review it is believed that answering these questions will create an opportunity to generate new knowledge in the field of in-process metrology.

3.4 Research Methodology

This section explains the methodology used to achieve the aim and objectives of this research based on the scope outlined in this chapter. A deductive approach was selected to address the defined research aim. A deductive approach allows for the gathering of information from state-of-the-art literature and on relevant theoretical ideas, in order to then be able to create a hypothesis that will then be tested against an empirical data set. Once this data has been gathered and analysed using appropriate methods the hypothesis will then be confirmed or rejected and the theory will be revised accordingly (Bryman, 2016). The methodology based on this approach can be broken down into five stages as shown in Figure 19. The first stage is understanding the capabilities and limitations of the current AR and MR technologies, as well as understanding the requirements of the metrology tools and current inspection process for LVM. The second stage is the specification of ISLVM. The third stage is the creation of prototypes to implement the ISLVM. Once a prototype has been selected, stage four addresses the design of the experiment for the verification and validation of the ISLVM. Finally, stage five is the analysis of the data captured in the experimental stage. These five stages are further explained below:

I. **Understanding of Current Capabilities, Limitations, and Requirements**

   The focus of this stage is to understand the capabilities, requirements, and limitations of AR, MR, and metrology equipment, and how they are implemented in industry. This will establish the foundation of what has already been achieved with existing technology, which in turn will give an indication as to how AR and MR can solve current challenges in LVM. Firstly, a review of the state-of-the-art metrology best practices, current metrology procedures, standards, and results from industrial measurement-assisted assembly case studies will be performed (see Chapter 2). This review will clarify which metrology fundamentals, best practices, and standards could assist the ISLVM, as well as the specific timing or frequency of information delivery during verification or assembly. As well as academic literature, best practice guides from National Physical Laboratory (NPL), standard operating procedures from equipment providers, national and international standards, and industrial measurement-assisted assembly case studies will be used as information sources. The review will then extend to the use of AR technologies in manufacturing, verification and validation. This will help establish the current state-of-the-art, critique existing methodologies for later comparison and to gauge the levels of risk in this research, and also highlight opportunities resulting from gaps in the current research landscape.

To give well-informed assistance and guidance through an immersive system, the second step comprises LVM hardware training from expert trainers and users. This will include learning on how to use the Leica AbsoluteTracker AT401 (Leica, 2012), photogrammetry system Aicon DPA MoveInspect (AICON, 2015), CMM Global 071007 with a Renishaw retrofit , Romer Arm RA-7535 SE (Hexagon Metrology, 2011b) , Romer Laser Scanner CMS108 (Hexagon Metrology, 2011a), and metrology software like SpatialAnalyzer and Geomagic. The majority of the metrology equipment mentioned is identified in the literature review of Chapter 2, these are the enabling technologies within industrial LVM. The additional equipment mentioned was reviewed for completeness on inspection procedures. As such, an AR interface designed with this in mind offers an appropriate cross-section of the relevant technologies.

The third step contains pilot studies with current AR and MR technologies that will be used to verify that the prototype ISLVM meets a set of predefined requirements. These studies are used to better understand the limitations of existing technology, such that the final prototype is dependant only on existing capability and not on future hardware and software developments. Furthermore, these studies represent a feedback loop to permit iterative improvement of the prototype systems against the requirements. These studies are detailed in Section 5.3 and are a precursor to subsequent validation through experimental trails (see Section 5.4).

II. Specification of an Immersive System for Large Volume Metrology (ISLVM)

Once the current requirements for an inspection process are identified and the capabilities and limitations of current AR technology acknowledged, it is then possible to set the specification of an ISLVM system. Chapter 4 identifies the 5 key stages in an inspection process as well as the challenges. In addition to this, after each explanation of the key stages a description of how the ISLVM can improve each of the challenges encountered is presented.

It is important to mention that this stage only specifies the full potential of an ISLVM, which will be further validated in stage four.

III. Development of ISLVM Prototypes

This stage will focus on developing the prototypes in the Unity game engine (Unity, 2017) in conjunction with the HoloLens MR hardware. Unity was selected as the development platform due the HoloLens having its core functionality, tools, scripts, and libraries developed in this platform by

Microsoft. This development will be layered insomuch as smaller prototype systems will be developed for individual tasks and capabilities, which will later be combined into a larger system that can perform metrology tasks by communicating with measurement equipment. Each of these prototypes will then be tested in order to gauge the effectiveness and usability of the system, as well as to receive feedback on the prototypes. This process will be repeated until a design of a prototype that implements the core features of the ISLVM is obtained. These prototypes are further described in Chapter 5, Section 5.4.

IV. Design of the Experiments for Verification and Validation of the ISLVM

After identifying the required ISLVM components and the roles of each component, it is then possible to start the design of a prototype that considers these findings and that can be tested through defined case studies. Stage four takes the final prototype obtained from Stage three in order to design the verification and validation of the ISLVM. Tests will be undertaken in a metrology lab where participants with no previous knowledge with a laser tracker will be asked to take measurements of an assembly using the laser tracker and metrology software. The ISLVM will guide the participants through the use of the hardware and software. Chapter 5 documents the specific experimental methodology developed to validate the ISLVM by comparing and contrasting with existing best practice methods (paper and digital manuals).

V. Data Analysis of Experiments

Stage five will focus on how the data captured from the experimental phase will be analysed. The data collected from the comparative study in stage four will be used to test the hypothesis and the core features of the ISLVM, further detailed in Chapter 5, Section 5.5. How the data will be collected, and why these methods will be used are described in Chapter 5, Section 5.8. Statistical analysis will be performed on the data in order to identify the significance level of each of the effectiveness and usability variables. The methods that will be used mimic the methodologies from similar studies for ease of comparison. These are explained in detail in Chapter 5, Section 5.9 and the results obtained from the data analysis are presented in Chapter 6.

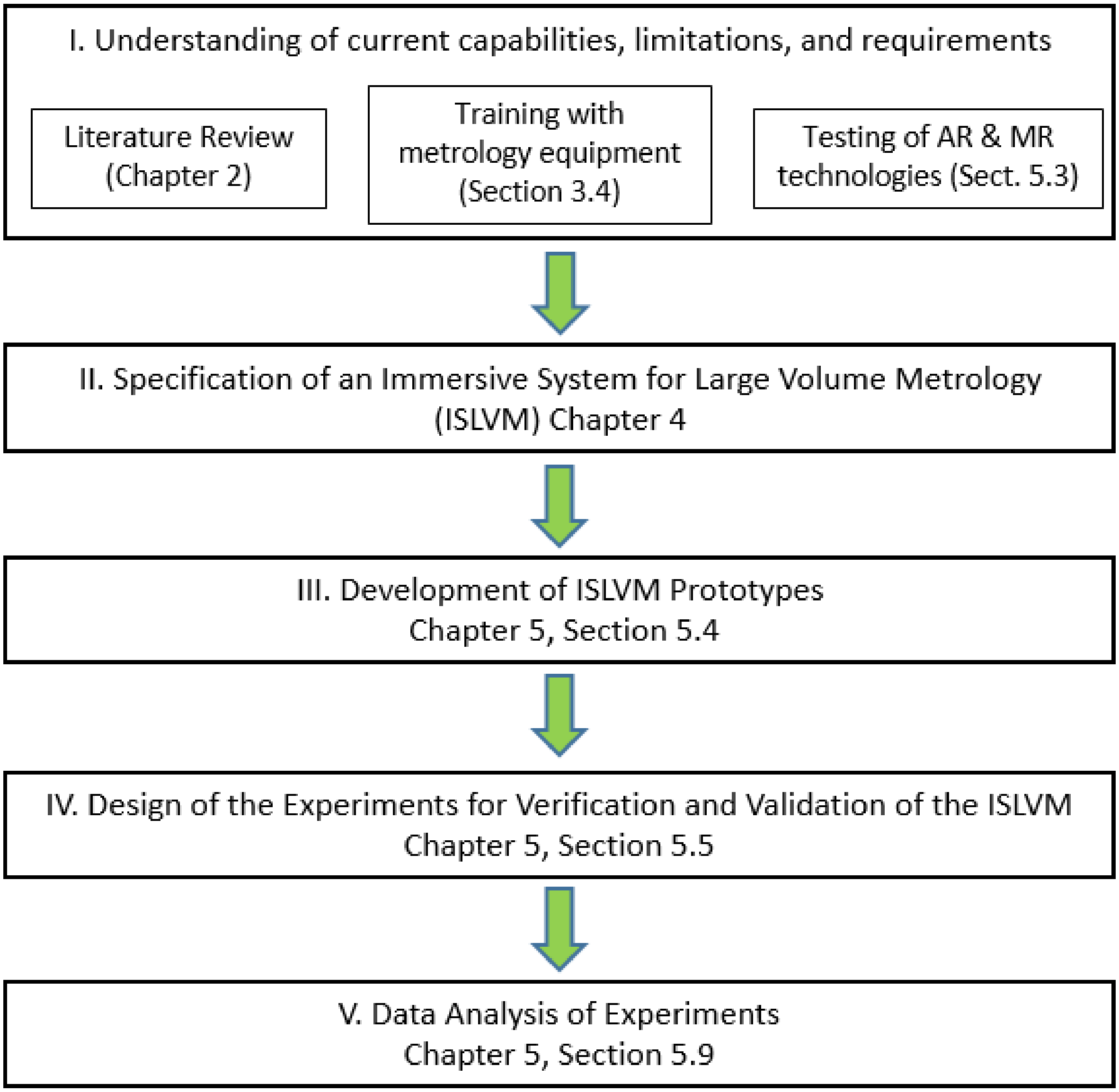


Figure 19 - Research Methodology

4. Specification of an Immersive System for Large Volume Metrology (ISLVM)

4.1 Introduction

In this chapter, the specification of the ISLVM will be presented. The gaps identified in the literature review have been used to establish a set of requirements for the design of the complete ISLVM. An inspection process has been divided into 5 key stages that an operator will typically undertake at the time of assembly verification. It is in each of these 5 stages where the requirements for the ISLVM have been broadly specified. It is important to mention that the ISLVM has been specified for two type of users: an assembly operator who is not an expert in metrology and an expert metrologist. The first case relates to users that normally perform tasks other than inspection, meaning that they do not appreciate the fundamental concepts of metrology or LVM best practices. The user in the second case has a full understanding of metrology fundamentals and best practices but could benefit from the unique set of tools offered by the ISLVM described in the following sections. Further details regarding the users of the ISLVM can be found in Chapter 5, Section 5.4.

4.2 Requirements for ISLVM

These 5 key stages represent a typical metrology process flow for the inspection of an assembly. The 5 key stages consist of hardware set-up, instrument location in the 3D CAD volume, measurements, data analysis and interpretation of results, and documenting of the metrology results. Each stage is further divided into circumstances that can affect the inspection process. Once these circumstances have been further detailed, a brief description on how the combination of metrology and MR can enable an ISLVM to solve these issues is presented.

4.3 Hardware Set-up

Hardware set-up is the first of the five stages, and it will address three main areas described below:

i) Evaluation of potential measurement uncertainty sources: An evaluation of the measurement area must be undertaken, identifying and assessing any factors that can affect the measurements and induce errors. As specified by GUM (JCGM, 2008) all systematic and random sources of error must be accounted for. In the literature review in Chapter 2, 10 potential components of uncertainty were defined (ISO 14253-2:2011, 2011). The first of these potential sources is the environment, where fluctuations in temperature tend to be the main sources of environmental uncertainty. Any factors that can affect the temperature, such as heat sources and open windows, need to be taken into account. Other causes of environmental uncertainty can include vibration sources, changes in humidity, stability of the instrument location and position, cleanliness of the area and component and lighting. These factors can have an impact on the assembly, as well as on the measurements and performance of the instruments. With an ISLVM approach, the MR technology can graphically display the changes in the environment and the potential impacts that these changes would have on the measurements. This is can be achieved receiving information from the environmental sensors dedicated to these factors. These would be displayed in the user's field of view in the form of digital augmentations making the monitoring of uncertainty sources immersive.

ii) Unpacking: This investigates hardware unpacking and assembly, activation and connection to the required metrology software. It is expected that an operator using a metrology instrumentation will be trained in these aspects. However, due to the complexities of metrology instrumentation, there are several key steps that must be undertaken before the instrument is used. For example, balancing of laser trackers or, in the case of photogrammetry, guaranteeing that the focal distance of the camera is not changed nor altered. Since the focal distance in photogrammetry is due to the principle distance, which is a calibration parameter, 'c', altering this distance will disrupt how measurement calculations are made. The ISLVM can incorporate image recognition through the MR technology, which could enable ID target detection and determine which instrument is going to be used, and where it is going to be placed. Thus, a step-by-step immersive system guiding an operator through the necessary requirements of each instrument can be displayed through the MR device. As the operator progresses through each stage, pictures can be captured and logged with the headset, and reports generated and sent to production managers as a means to guarantee that an instrument has been deployed correctly.

iii) Instrument set-up: Once the instrument has been assembled and connected to the required metrology software, there are several steps that must be completed before the operator can proceed with measurement capture. The steps vary depending on the instrument that is used. For example, in order to obtain the greatest accuracy from a laser tracker, it needs to warm-up for approximately 20 to 30 mins before measurements can be taken. After the warm up cycle, the operator carries out the necessary field checks. This ensures that it is working within its specification limits and consequently there is less uncertainty regarding obtained measurements. Some of the field checks performed include an ADM two face check, a scale bar check, and an angular accuracy check. An example for photogrammetry would be that scale bars and targets need to be positioned in certain orientations, and positions to obtain accurate measurements with less uncertainty. This is a crucial step that can have a considerable impact on the measurements. To guarantee that these steps are carried out correctly, the ISLVM can display appropriate instructions to the operator to ensure that the metrology instrument is used correctly. The instructions would depend on the ID target that is recognised (an in-built functionality of the MR technology). Consequently, the ISLVM would be aware which equipment is being used and where it is going to be used.

4.4 Instrument Location in the 3D CAD volume

When a measured point is recorded, it's X, Y, Z coordinates are given with respect to the instrument's reference system. Once the metrology instrument has been correctly set up there is a further stage that needs to be addressed before measurements of the assembly can be taken. This is the alignment of the instrument within the 3D CAD volume. The metrology software does not know where the instruments are located or positioned in the workspace, relative to the assembly that needs to be verified. To achieve this, a reference network needs to be defined.

i) Reference Network set-up: A reference network is a constellation of points carefully designated around the assembly. The main purpose of a reference network is to enable alignment of the measurement instrument in the digital software workspace to correspond with the instrument in the real world. Once the reference network has been set and specified in the software, the instrument is aligned by taking measurement points of the reference network. The software is then able to position the instrument in the digital workspace to correspond with its real-world position. Where these points are specified, and how many need to be designated, depends on the size of the assembly and where the assembly is located. Instrument alignment is a crucial step in the measurement process and, if not performed correctly, measurement post-processing analysis will be incorrect. Figure 20 helps illustrate the concept of alignment. Using an ISLVM approach, the operator can be systematically guided through the process of setting up a reference network and then conducting alignment. Instructions can be issued to the user through an immersive system using a MR headset. This would increase the probability that the procedure has been performed correctly, thus reducing errors in the inspection process.

Figure 20- Left, unaligned measurements. Right, measurements after alignment (Kinematics, 2013).

4.5 Measurements

Once the instruments have been set-up and aligned properly, the third stage is to take the measurements of the assembly to be inspected. The ISLVM has the potential to assist with the measurement stage in 3 areas:

i) Measurement guidance: Currently, when an operator wants to perform an inspection process they follow a predefined guide that details the procedure / steps, specifying the points to be measured. This manual could be printed or in an electronic format. This means that the operator needs to be looking back and forth between the manual and the component to locate the measurement areas. Also, this allows room for interpretation on where the correct measurement area is, making measurement errors more likely. An ISLVM approach can guide the operator through the complete measurement process by digitally displaying the positions that need to be measured on to the assembly using a MR headset. This would remove the need for any interpretation, or for the operator to locate the correct position to measure as the defined position will be digitally displayed on the assembly component. This will reduce the likelihood of an incorrect position being measured.

ii) Presentation of data: Currently, when an operator is performing measurements, captured data is displayed on a computer screen. Normally for large volume applications the screen is often positioned far from where the measurements are being taken. This results in the operator not being able to see what measurements have been taken so far. To see progress, they would need to stop taking measurements and walk to the screen. When taking a large number of data points, the operator could lose track of what they have done, or not realise that a measured point was not taken properly. There is a key difference between simply taking a measurement and taking the correct measurement. If a point is not measured correctly it results in larger uncertainty values in the measurements. Using an ISLVM approach, the points that have already been taken can be displayed graphically on the assembly through an immersive MR headset, thus eliminating the need to stop the measurement process to check progress. This would reduce the probability of the operator losing track of measurements and further reduce the likelihood of committing errors during the measurement process.

iii) Environmental checks: As mentioned in the hardware set-up stage, the environment can have an impact on the inspection process if it is not continuously assessed and evaluated. If the correct sensors, and measurands are set in place, these could feed the ISLVM in real time. This would allow the interface to detect when the current conditions of the environment have changed affecting the measurement process and data gathered. It could then warn the operator through the MR headset. These changes can be due to climate changes (e.g. doors opening) causing changes in the temperature and humidity, vibrations, and other events that have the capability of altering the environment and thus the measurements as well. Using an ISLVM, warnings can be issued to the operator in real time through the headset to stop the inspection process and provide details on environmental changes. Furthermore, if the factor changing the environment cannot be corrected, the ISLVM can have an option to proceed with the measurements and at the same time it can display through the MR headset what the likely effects on the assembly and on the measurements will be due to the change in the environmental conditions. Thus, allowing a full immersion of the user in the real-time conditions of the environment. This could reduce the probability of taking measurements under incorrect environmental conditions, or under unknown circumstances that are affecting the inspection process, thus allowing for a more accurate and reliable verification.

4.6 Data Analysis and Interpretation of Results

As mentioned in Chapter 2, Section 2.5, and further discussed as one of the research objectives in Chapter 3, the ISLVM will present captured measurement data in a meaningful way, allowing the operator to make informed decisions. This fourth key stage details how the ISLVM will present data captured during the measurement process. Currently, an operator has to complete the inspection process and then go off-line to analyse the captured measurement data using appropriate software. If there are problems with the collected data, the operator will re-take the measurements. If no problems are detected, such as incorrect points being measured, the operator then proceeds to analyse the data and interpret the results to see if the assembly conforms to the specification.

As the MR headset will be interacting with the metrology hardware and software, it will have access to the information that is being captured as the operator progresses through the inspection process. It will therefore be possible to take each point that has been measured, analyse it and display if it is the correct point immediately. It will state if the point was measured correctly, and if it is within tolerance. This can be achieved by using automated metrology software-driven scripts that, in conjunction with an immersive system displayed through a MR headset, can make it possible to display this information to the operator, directly during the inspection process saving time and money.

The results from the inspection process can be presented through the MR headset in a number of ways: with colour coded spheres, text, arrows, pictures, or 3D models. Which colours to use and what element to present it with depend on the application, as lighting conditions and instruments can have an effect on how the information is displayed.

Once the operator has completed the inspection process steps, instead of needing to look at the results on the screen of a laptop, the results of the analysis can be projected directly on to the assembly via the ISLVM with the use of the MR technology. This enables the operator to see on the real component which areas are outside of specification and by how much. As well as helping with the visualisation of results, an ISLVM approach could engage with these results by changing how they are displayed. For example, with the help of the MR technology, it could be possible to modify a mesh that had been projected on to the component to observe potential changes and the impacts of these modifications on the analysis. This enables a continuous loop for performing actions, analysing and interpreting results, which has the potential to reduce inspection time and enable the operator to make qualified and informed decisions.

4.7 Documenting the Metrology Results

The final key stage investigates how an ISLVM approach can improve current metrology process documentation. Current best practice consists of documented procedures that outline the necessary steps to complete a given verification process, resulting in an inspection report. This report could document potential issues with a description of what is causing the non-conformance. These reports are difficult to interpret by non-experts. Also, there is no way to guarantee that the inspection process was carried out as defined in the best practice documentation. An ISLVM approach could record each step, or the desired steps as the operator progresses through the inspection process. In addition, images and video can be recorded and be sent to production manager for further verification to enable reductions in errors or malpractice. Furthermore, MR technology could enable a direct line of communication between the manager and the operator through which the manager can see in real time what the operator is seeing in order to provide additional guidance if required. This way, the manager could be immersed in the environment in which the operator is in, and provide a more accurate guidance.

At the end of the inspection process, a report can be generated detailing each specific action that was taken during the inspection procedure. This report can be used in the future if any issue arises and more specifically if any corrective measures were taken. Providing that the components or assembly being inspected meet the requirements specified, a report with the steps taken can also be generated. This can be used to guarantee that the operators are following the inspection process. An ISLVM approach can include a feature to enable operators at the end of each report to comment on the inspection process with holograms and real footage generated with the MR technology to highlight issues that may require improvements. This information can be sent to the corresponding engineering group for further analysis and process improvement.

4.8 Functional View of the ISLVM

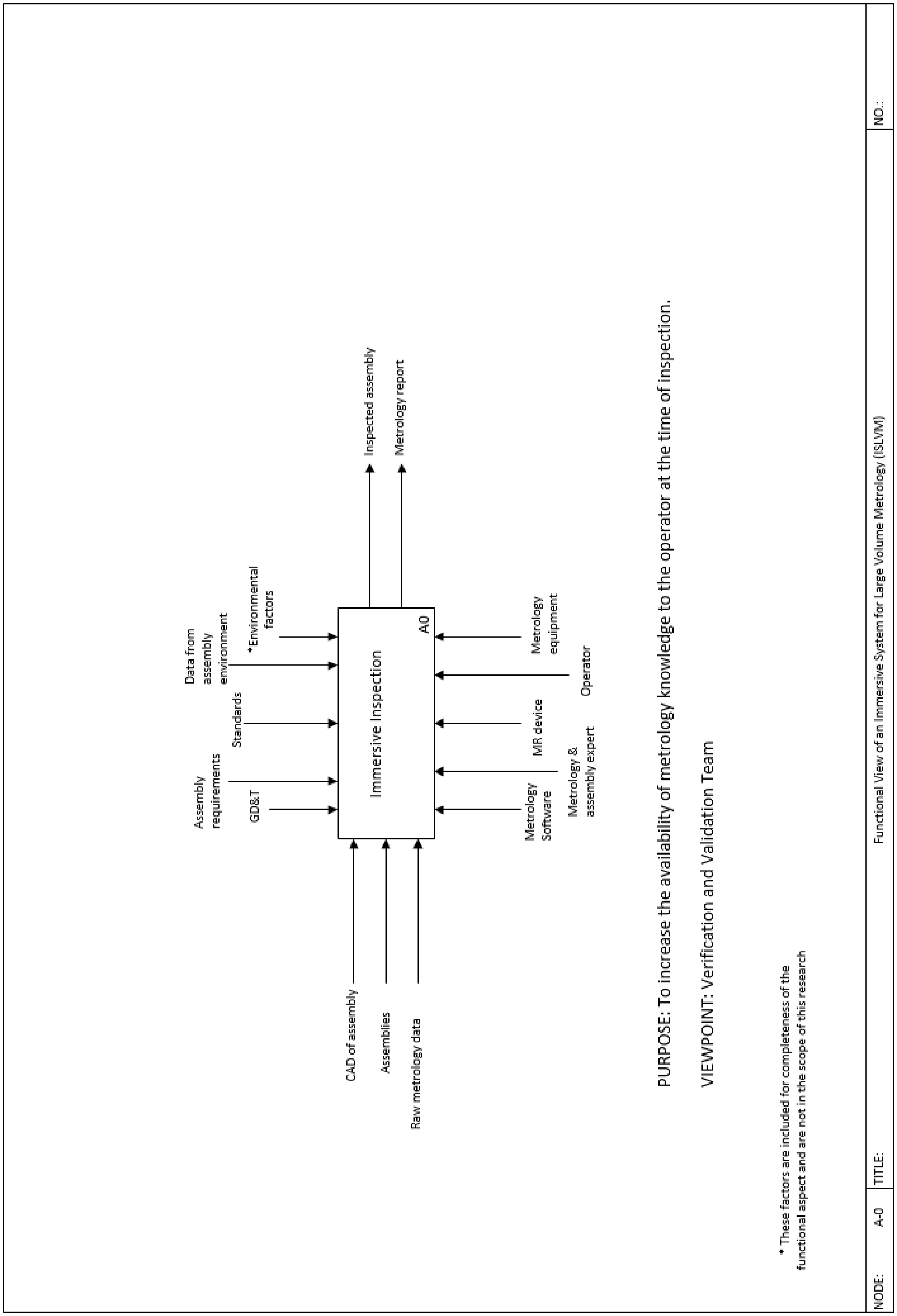
A functional view of an ISLVM approach is depicted as an IDEF0 diagram (A0), detailing the inputs, outputs, controls and actions. Following these diagrams an illustration is also presented regarding how the user, hardware, and software interact during an inspection process.

Figure 21 presents a general overview of all the components that integrate an immersive inspection. The IDEF0 diagram in Figure 22 shows the main activities (A1) broken down into specific activities with their respective components. Each activity is described below:

1. The first activity is the creation of an MR suitable verification and validation plan. The inputs required are the specifications of what needs to be measured. This could be in the form of CAD drawings, or nominal data to which the measurements will be compared to. The controls are the assembly specification requirements, metrology standards (GUM and ISO 14253-2:2011), environmental information, and the GDT specifications of the assembly. The mechanisms are a MR device with its

respective software, a metrology and assembly expert, an operator that can provide assembly input and of the environment and a computer with the required metrology software and interface to be able to communicate with the MR device. The output obtained would be a MR inspection plan that is designed to be used in collaboration with a MR device and the metrology equipment. This output then becomes an input for Activity 2.

2. The second activity is the display of the metrology guidance information. The inputs required for this activity are the MR compatible inspection plan that was produced in Action 1, and the raw metrology data captured from the metrology equipment being used in Action 3. The controls are environmental data that could disrupt the measurements. The mechanisms are a MR device, environment sensors (thermocouples, humidity and pressure sensors, and if needed vibration detectors), and a computer running the software interface that enables the two-way communication between the MR device and the metrology equipment, as well as processing of the data captured from the environment. The output generated would be the information needed by an ISLVM to guide the operator through an inspection process.
3. In the third activity, the measurements needed to inspect the assembly are performed. The input required is the physical assembly to be inspected. The control is an ISLVM, the output from Action 2, regulating and guiding the operators throughout an inspection process. The mechanisms are the MR device, the metrology equipment, the operator, and the computer that acts as the interface between the MR device and the metrology equipment and software. There would be three outputs from this action. The first is raw metrology information that is being continuously fed as an input to Action 2. Enabling the ISLVM to display accurate, real-time information to the operator in order for them to successfully complete the inspection process. The second output would be an inspected assembly. The third output is a metrology report indicating the result of the inspection. This output can be fed back as an input to Action 2, as displaying the results on the assembly can assist with interpretation of results.



PURPOSE: To increase the availability of metrology knowledge to the operator at the time of inspection.

VIEWPOINT: Verification and Validation Team

* These factors are included for completeness of the functional aspect and are not in the scope of this research

Figure 21 – Functional view of ISLVM

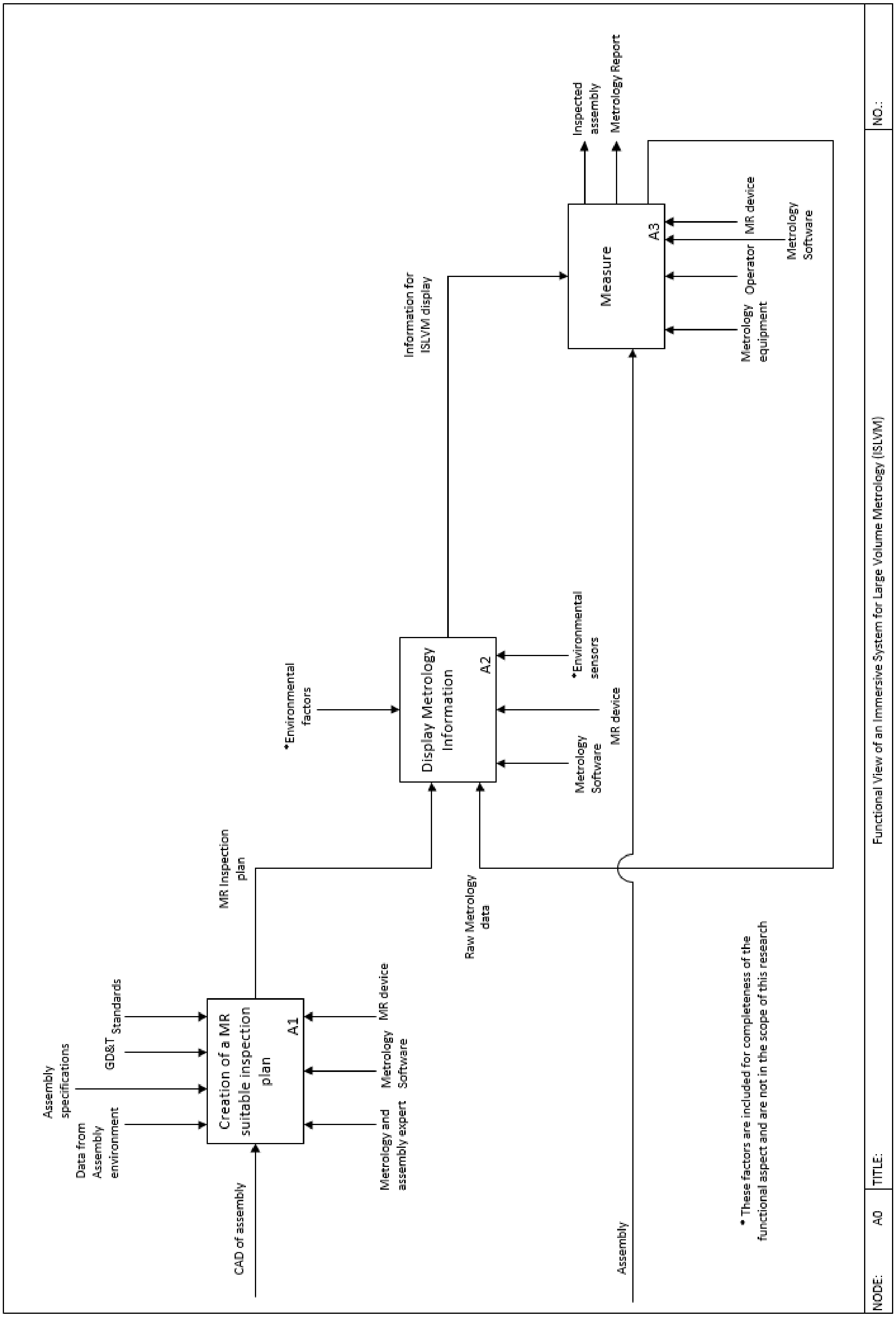


Figure 22 - Detailed representation of ISLVM

In order to simplify the process for the operator and allow the user to concentrate on the inspection process, the operator needs to primarily interact with the MR device, while limiting the interaction with the laptop. This will allow the operator to focus on using the metrology hardware and interact with the guidance presented by the MR device. Control of metrology data, as well as capturing and monitoring of environmental data, instructions that need to be sent to the metrology hardware to perform a certain action and to the MR device to provide the appropriate guidance, will be carried out automatically in the laptop without disrupting the operator. Figure 23 helps illustrate these interactions.

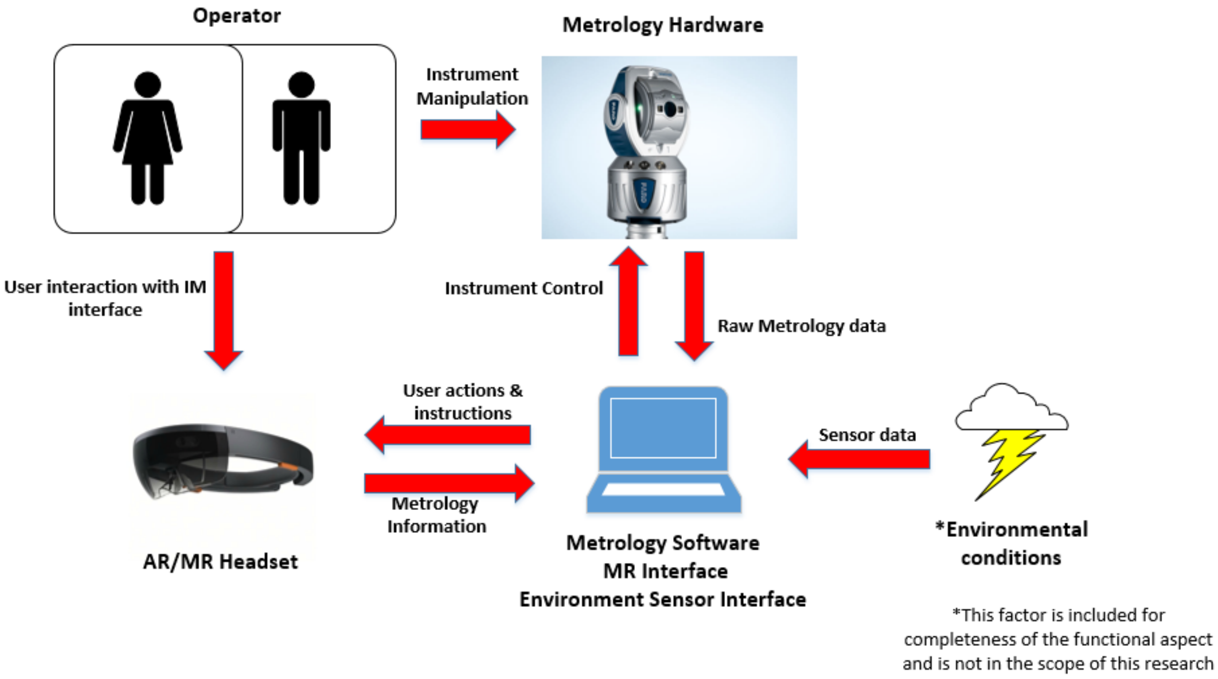


Figure 23 - Interaction between the components of an ISLVM

5. Prototype Implementation of an ISLVM

5.1 Introduction

This chapter details the implementation of an Immersive System for Large Volume Metrology prototype (ISLVM). This will consist of, assessing the performance of an ISLVM in an assembly inspection process when compared to paper and digital manuals through a series of defined experiments.

5.2 Stages for Implementation of an ISLVM Prototype

A total of seven stages have been defined to implement the ISLVM prototype. These seven stages are detailed below (and in Figure 24.) and are based on the chronological order in which the ISLVM requirements need to be solved.

i. Selection of widely used LVM instruments (e.g. laser tracker) and MR equipment that exhibits sufficient capability to realise the ISLVM. Particular attention is given to compatibility between the LVM instruments and the MR equipment, via an interfacing metrology software.
ii. Development of software prototypes to confirm specific and necessary capabilities of the MR headset via the Unity game engine. Additionally, testing of the interfaces between the metrology instrument, the metrology software and the control of the instrument via the MR headset were tested. Prototypes included both software development and also experimentation to confirm that the vision of the ISLVM prototype could be delivered through the chosen hardware and software combination.
iii. Design of experiments for the verification and validation of the ISLVM. Experiments were designed to compare the user performance with the ISLVM prototype and current best practice.
iv. Participant selection for the experiment, where participants were chosen based on a set of criteria that would most accurately reflect the end users of the ISLVM.
v. Conduct the verification and validation experiment(s)
vi. Evaluate the data captured from the tests performed in stage five. The data captured is defined in such a way that a comparison against studies defined in the literature is possible.
vii. Data analysis of the experimental tests. Previous studies from the literature serve as the basis to define the data analysis that should be performed.

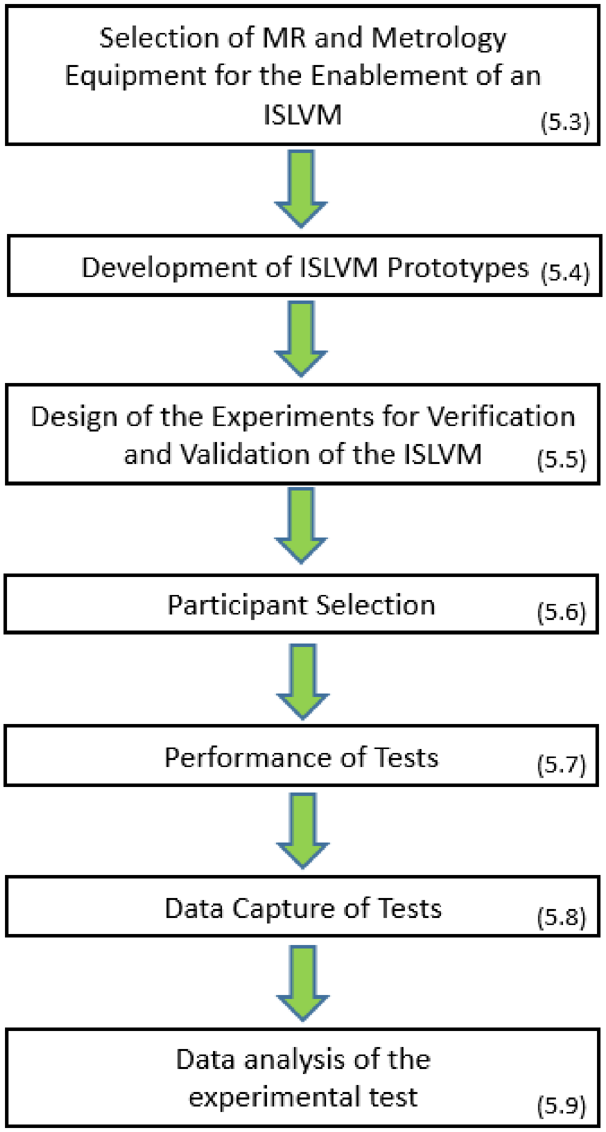


Figure 24- Stages of the experimental work

5.3 Selection of MR and Metrology Equipment for the Enablement of an ISLVM

A key factor in the development of the ISLVM prototype is the appropriate selection of an AR device. The following are the key elements that the AR device must satisfy:

- While the operator is using the device, they need to have both their hands free at all times in order to be able to complete the assembly inspection process.
- The operator should have the option to move freely around the assembly area without losing sight of the guidance instructions and measurement data.

- Provide the user with full visibility of their surroundings while still projecting digital information on to the working area.
- The device must seamlessly interact with the user and the processing platform to enable measurement data to be displayed in real-time so that measurement guidance can be provided to the operator throughout the inspection process.

In the literature review (Chapter 2) three types of digital realities were discussed. These were Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). The types of displays for VR and MR are predominantly head mounted displays (HMD), while AR can produce augmentations on hand held screens, HMD, and projected AR. The reader is referred to Chapter 2 for further specific details on the differences between the devices.

Based on the first key element that requires the operator to be continually hands free, AR with hand held displays such as tablets and smart phones are not suitable. Smart devices generally need to be continuously pointed in the direction of interest to be able to recognise a target and project the desired digital content. This would require the operator to be interacting with the device screen to see the augmentations and be looking away from the assembly area. This could result in the operator being distracted from the task, requiring them to use their hands for purposes other than the measurement process.

The second key element specifies that the user should be able to move freely and observe the assembly area without losing sight of the digital augmentations. This eliminates projected AR as the cameras and projectors are fixed in the assembly line as well as the digital augmentations being fixed to a certain area at any given time. This requirement also eliminates VR headsets, as at the time of the writing of this thesis all current VR headsets need to be connected to a computer; thus limiting the user’s movements. The remaining technologies that satisfy the two requirements (movement and hands free operation) are AR HMD, and MR.

The third key element further eliminates the possibility of using VR for this application. The main purpose of this technology is to isolate the user from the real world in order to immerse them into a digital world projected through the headset. This can potentially be a serious health and safety risk in an assembly area where there is continuous movement of people and machinery. Both AR HMD, and MR headsets do comply with this requirement as the headset screen is a see-through display.

The fourth and final key element specifies that the device needs to interact with the user and the laptop concurrently, while being able to display real-time measurement data in order to guide the operator through the assembly inspection process. At the time of the selection of the device (approximately July-August 2017), the only AR HMDs available for the consumer market were the Epson Moverio BT-200 (EPSON, 2017), Vuzix M-100 (Vuzix, 2017), Sony SmartEyeglass (Sony, 2017), and the Optinvent Ora-1 (Optinvent, 2017). These headsets have a single camera, a gyroscope, an accelerometer, a GPS, and a compass to track location and surroundings. These headsets work with an image recognition software that detects a specific image, targets or locates it and then displays the desired digital content in that particular location. The interaction with the digital content is through buttons on the headsets, a separate control unit, through the users' phone and, in some cases, through tracking of gestures and voice recognition. Before purchase of a headset, preliminary tests were carried out with a Samsung Tab S2 tablet, which has the same components (camera, gyro, accelerometer, etc.) as the headset, except the display is on the tablet's screen instead of on the glasses. The tablet did not have any of the voice or gesture tracking to interact with the digital content. This was not a concern as the main focus of the tests was to observe how the image recognition performed under a diverse set of lighting, targets, and moving conditions. The image recognition software packages that were used for these trials were the Wikitude (Wikitude, 2017) , Vuforia (Vuforia, 2017) and ARToolkit (ARToolkit, 2017) SDKs. These are freely available versions and provide tutorials on how to use their image recognition software to augment images in the desired environment. Table 1 provides a comparison between these three packages. After running a series of tests with different targets, it proved challenging to recognize a target and maintain the augmentation from different angles, lighting conditions and distances. Also, the number of features on a specified object, and tablet movement caused further issues. It was found that the images would stutter, disappear and re-appear, or take several attempts at recognizing a target before the digital augmentation would appear. The best results were obtained under good lighting conditions, with the tablet close to the desired target and perpendicular to it, and when it remained as static as possible. After these tests, it was concluded that the headsets (mentioned above and comparable to a tablet) could potentially be used for an ISLVM prototype implementation. However, it would be difficult in an industrial environment due to the lighting conditions and constant movement of the operators and assemblies.

Table 1 - Comparison of used AR image recognition software packages.

	Vuforia (Vuforia, 2017)	**ARToolKit** (ARToolkit, 2017)	**Wikitude** (Wikitude, 2017)
Tracking Capabilities	The tracking and recognition of targets is affected by colour on the targets. Struggled heavily with black and white images.	The tracking and recognition of targets is colour neutral and it can detect black and white targets	Colour did seem to affect the tracking and recognition of targets with colour having better results.
Stability and Quality of Rendered Images	Good stable images and quality of the rendered augmentations.	The rendered images are generally jittery and of less quality.	Good stable images and quality of rendered augmentations.
Level of Programming Knowledge Required	No expert level of programming required.	Major knowledge and effort required to develop a similar app as it counterparts.	Medium level of programming required.
Capability of Handling Large 3D Images	Good stability and quality of large 3D augmentations	Large 3D augmentations are jittery, and the quality of the image sis less than its counterparts	Good stability and quality of large 3D augmentations
Type of Support	Commercial support, tutorials, and documentation	No commercial support, only forums and documentation	Commercial support, tutorials, and documentation
Recognition of 2D Images	It is supported	Images generally have to have a black border around them	It is supported
Recognition of 3D Images	It is supported	NOT supported	It is supported (Beta version)
Geo-Location (GPS)	It is supported	NOT supported	It is supported
Cloud Recognition	It is supported	NOT supported	It is supported
Cost	Free (watermark) + Commercial SDK option	Open Source	Free (watermark) + Commercial SDK option

At the time of writing this thesis the only purchasable MR device on the market was the Microsoft HoloLens (Microsoft Hololens, 2017). A full description of the hardware of the HoloLens and its capabilities are described in the literature review in Chapter 2. It is important to mention that the HoloLens is an untethered device with 4 environment understanding cameras, 1 depth camera, 1 2MP photo / HD video camera, mixed reality capture sensors, 4 microphones, 1 ambient light sensor, capability for spatial sound, gaze tracking, gesture tracking and voice support, and a custom-built Holographic Processing Unit (HPU). These features provide robust real-time tracking of the user's movements, voice, and its environment to not only display holograms on their surroundings but be able to interact with the holograms, which are then able to adapt to the changing environment. It was determined that the HoloLens was the most suitable device as it met the 4 key elements for an ISLVM implementation.

After the MR device was selected, the metrology hardware that would be used for the experimental test was the Leica laser tracker. The model used was the AbsoluteTracker AT401 (Leica, 2012). The main reason for this choice is that the laser tracker has been the instrument of choice in large volume metrology when it comes to high accuracy product conformance verification, tool setting, and jig verification (Francis *et al.*, 2016). SpatialAnalyzer (SA) is used as the metrology software as it works directly with the laser tracker. A full description of SA is provided in Chapter 2.

The laptop that was used was an Acer Aspire V 17 Nitro – Black Edition (Acer, 2017). The specifications for the laptop are an NVIDIA GEFORCE GTX 960M graphics card, a 17 in display, an intel core i7 procesor with 16GB of RAM, and a 64 bit Windows 10 operating system. This laptop was chosen because of the display size, but more importantly for the graphics and processing power that it has.

The hardware in Figure 23 has been defined for an instance of the ISLVM implementation prototype, excluding the enviornmental sensors as this is outside the scope of this research. The enviormental sensors would be able to provide current data on the assembly enviornment and be able to detect changes that can affect either the assembly or the inspection process. Ideally, these sensors would be thermocouples placed at different positions to detect temperature gradients or sudden changes in temparature, vibration sensors to detect if there are any vibrations that can affect the measurements, and sensors that can detect changes in pressure and humidty.

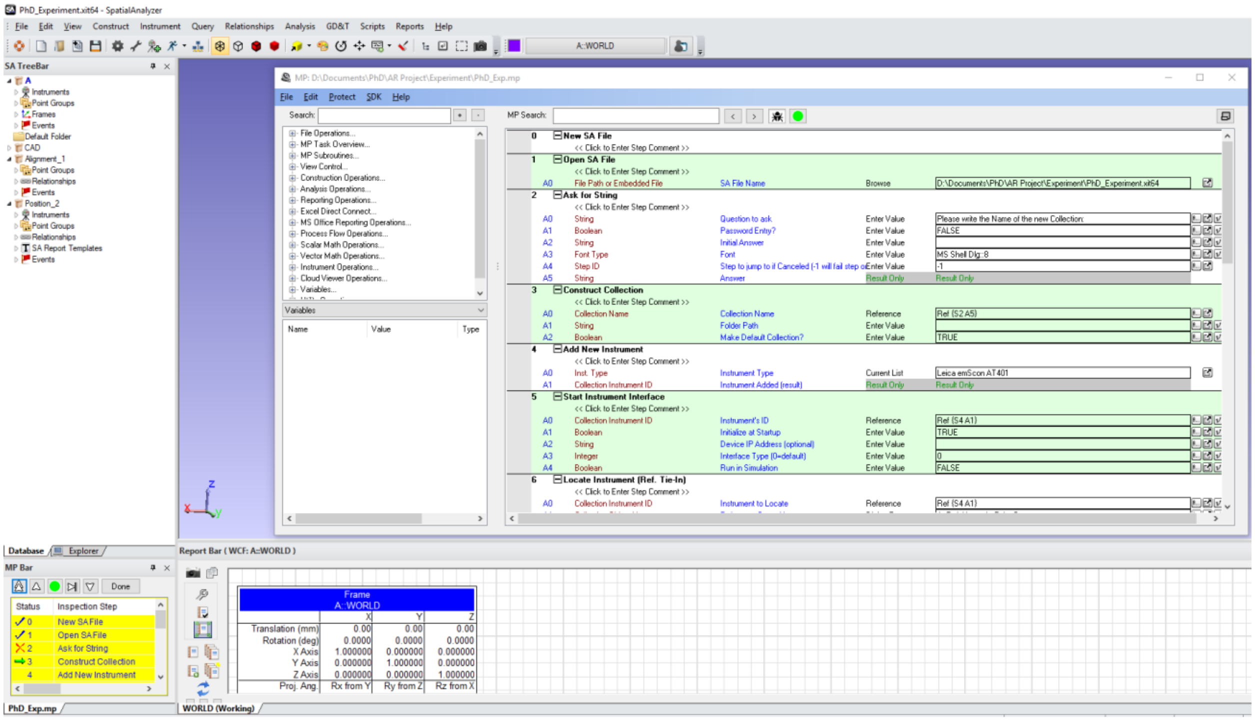
5.4 Development of ISLVM Prototypes

Once the MR hardware and the metrology equipment was selected, it was then possible to start with the design of the prototype that will test the ISLVM. Before the design of the prototype was started, it was important to define the intended user, as this factor has a considerable weight on the overall design of the prototype. As mentioned in the introduction of Chapter 4, there are two type of users of the ISLVM. One is an expert in metrology and the other is not an expert in metrology. However, these two users are intended for the complete implementation of the ISLVM, as described in Chapter 4. As mentioned in the scope of the research, and further detailed in Section 5.5 of this chapter, the prototype defined in this research is not the full implementation of the ISLVM. Therefore, this prototype has been designed only for non-expert metrologists. This is because it is more challenging for a novice user to perform at an enhanced level, rather than increasing the consistency of expert users. The novice user would be an operator who normally performs assembly tasks or any other task apart from verification and validation of components. Although, it could also be a novice metrologist. Therefore, these operators would need step-by-step guidance on how to properly conduct an inspection process. This should be accompanied by explanations of why it is that they are doing each step, and lastly a means to guarantee that they have done what has been instructed with the quality required.

This section focuses on developing prototypes in the Unity game engine (Unity, 2017) in conjunction with the HoloLens MR hardware, SpatialAnalyzer (SA) and the laser tracker. These prototypes were designed within this research and were not taken from other platforms unless otherwise stated. Unity was selected as the development platform due the HoloLens having its core functionality, tools, scripts and libraries developed in this platform by Microsoft. This development will be layered insomuch as smaller prototype systems will be developed for individual tasks and capabilities, which will later be combined into a larger system that can perform metrology tasks by communicating with measurement equipment. The development of prototypes was completed in four steps. The first step was the development of the metrology script, used to control the laser tracker and SA. The second step was the development of the MR user interface. The third step was the integration of the metrology hardware and software with the MR equipment. The fourth step was the testing of the prototype. These four steps will be further explained below:

i) Development of the Metrology Script

As mentioned in Chapter 2 (Section 2.3.3), in order to be able to conduct an inspection process and be able to control the metrology equipment, it is necessary to use a metrology software that acts as an interface between the user, the assembly and the equipment. It is in this software that the measurements are recorded. It is then possible to import CAD models of the assemblies to perform analysis on the data captured. SA has a scripting feature that allows the user to automate steps that can make the inspection process more efficient. Figure 25 shows this scripting feature. Once the script has been completed in SA, it is possible to export the code in C++ to an SA SDK that can be added to any other programming environment. In this case it was added to Visual Studio (Microsoft, 2017b). In order for SA's SDK to be able to be used with Unity the code obtained in C++ from SA was then translated to C# as this is the programming language used in Unity. Hence, the final script for this prototype was developed using C# in visual studio in conjunction with SA's own SDK. This code automates steps that would need to be performed in SA to complete the inspection process. The steps that were automated were the set-up of the project in SA (importing the CAD model, the reference network, adding and initialization of the laser tracker), and other procedural tasks, including creating: relationships between measured points and nominal data, performing a best-fit and generating a report. The final script can be found in Appendix A.



```
0    New SA File
          << Click to Enter Step Comment >>
1    Open SA File
          << Click to Enter Step Comment >>
  A0      File Path or Embedded File    SA File Name                          Browse         D:\Documents\PhD\AR Project\Experiment\PhD_Experiment.xit64
2    Ask for String
          << Click to Enter Step Comment >>
  A0      String                        Question to ask                       Enter Value    Please write the Name of the new Collection:
  A1      Boolean                       Password Entry?                       Enter Value    FALSE
  A2      String                        Initial Answer                        Enter Value
  A3      Font Type                     Font                                  Enter Value    MS Shell Dlg::8
  A4      Step ID                       Step to jump to if Canceled (-1 will fail step oEnter Value    -1
  A5      String                        Answer                                Result Only    Result Only
3    Construct Collection
          << Click to Enter Step Comment >>
  A0      Collection Name               Collection Name                       Reference      Ref (S2 A5)
  A1      String                        Folder Path                           Enter Value
  A2      Boolean                       Make Default Collection?              Enter Value    TRUE
4    Add New Instrument
          << Click to Enter Step Comment >>
  A0      Inst. Type                    Instrument Type                       Current List   Leica emScon AT401
  A1      Collection Instrument ID      Instrument Added (result)             Result Only    Result Only
5    Start Instrument Interface
          << Click to Enter Step Comment >>
  A0      Collection Instrument ID      Instrument's ID                       Reference      Ref (S4 A1)
  A1      Boolean                       Initialize at Startup                 Enter Value    TRUE
  A2      String                        Device IP Address (optional)          Enter Value
  A3      Integer                       Interface Type (0=default)            Enter Value    0
  A4      Boolean                       Run in Simulation                     Enter Value    FALSE
6    Locate Instrument (Ref. Tie-In)
          << Click to Enter Step Comment >>
  A0      Collection Instrument ID      Instrument to Locate                  Reference      Ref (S4 A1)
```

Status	Inspection Step
✓ 0	New SA File
✓ 1	Open SA File
✗ 2	Ask for String
→ 3	Construct Collection
4	Add New Instrument

Frame A::WORLD	X	Y	Z
Translation (mm)	0.00	0.00	0.00
Rotation (deg)	0.0000	0.0000	0.0000
X Axis	1.000000	0.000000	0.000000
Y Axis	0.000000	1.000000	0.000000
Z Axis	0.000000	0.000000	1.000000
Proj. Ang.	Rx from Y	Ry from Z	Rz from X

Figure 25 - Scripting capability inside SA

ii) Development of the MR User Interface

The MR user interface was developed through the Unity game engine. Hence, there were two main goals that were set in order to have a working user interface. The first was to be able to project the desired holograms onto the real world in a way that it would make sense to the user without saturating the scene with information. This was achieved by gradually adding holograms to the different scenes that the user would be seeing. It started with the very basic figures to ascertain how the holograms were seen on the actual headset and in the real world, as there is a big difference between how things appear on a computer screen and how they are seen as holograms in the real world. For example, the first hologram that was added to a scene was a simple cube, then text and arrows. The number and complexity of holograms was then increased until the digital information projected to the user could be of use within an inspection process. Figure 26 shows some the holograms that have been added to the Unity scene, which will then be displayed through the HoloLens for the prototype being designed.

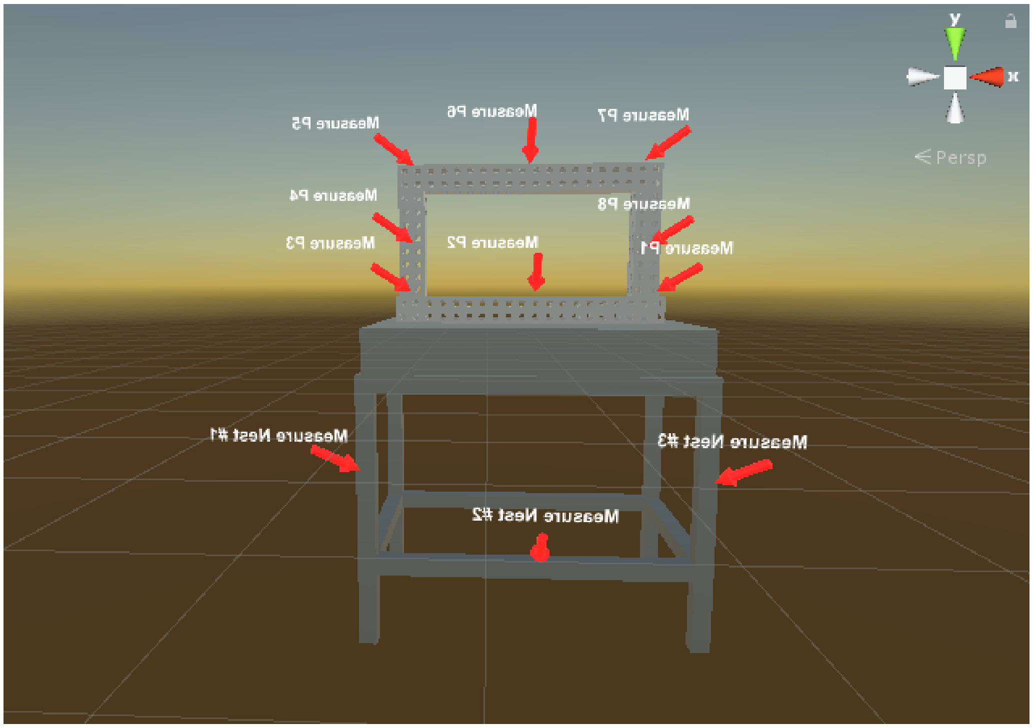


Figure 26 - Holograms added to a Unity scene which will be displayed in the prototype.

The second goal was to be able to interact with digital content. The method of interaction was voice commands, as this would free the operator's hands, enabling them to interact with the digital content whilst operating the metrology equipment. There was a need to understand how the voice command scripts developed by Microsoft functioned. Thus, the tutorial regarding voice commands for the HoloLens offered through the Microsoft Mixed Reality Academy (Microsoft, 2017a) was completed. These scripts and methods were then implemented into the prototype to see if the user was able to successfully interact with the digital content. Once this was achieved, a trial that tested different words was performed in order to define the words that worked the best. For example, the word "continue" was replaced by "next" due to it having a higher detection rate. After this, tests with different colleagues, each of whom had different accents, were performed to verify the robustness of the words selected. In addition, how well the user could interact with the digital content using these voice commands was evaluated. The necessary changes and adjustments from these test were made in order to have a final selection of words and methods to interact with the holograms. The list of the final voice commands used for the prototype can be found in Appendix B.

iii) Integration of the Metrology Equipment with the MR Equipment

Once the MR user interface was completed, the next step was to be able to integrate the metrology hardware and software (referred to as equipment) with the MR equipment. This would then create an immersive system that enables the user to simultaneously use the metrology equipment and interact with the MR device. The key challenge was to integrate the metrology script developed in SA with the MR interface and the voice commands from the HoloLens headset. This would enable the user to be able to control both SA and the laser tracker through voice commands. The first step to solve this challenge was to understand how the HoloLens enabled collaboration between other devices. It was then through a HoloLens tutorial script for a collaborative shooting game, which was modified for the purposes of this research, that communication between SA and the HoloLens was enabled. Tests were then conducted to find the correct method that would transfer the necessary information to control the metrology equipment, capture the results, and display them back to the user in order to guide them through the inspection process. After extensive testing, a system was developed that allowed the user to give instructions that controlled both SA and the laser tracker, capture the results of the action, and display the result to the user.

iv) Testing of the Prototype

Each of these prototypes were then tested by research colleagues in order to gauge the effectiveness and usability of the system, as well as to receive feedback on the prototypes. Adjustments were made after each test in order to improve the prototype. This process was repeated until a prototype that implemented the core features of the ISLVM was obtained. This final prototype is further described in the remaining sections of this chapter.

5.5 Design of the Experiments for Verification and Validation of the ISLVM

This section details the design of the tests that will be used to evaluate the ISLVM implementation prototype. In order to define the tests and provide validation, the research questions outlined in Chapter 3 will be used.

It is the author’s opinion that answering these 4 specified questions will validate the ISLVM. These 4 questions defined the experiment, and helped make the decision to exclude certain features of the ISLVM. The main features of the ISLVM that were omitted from the tests were:

- Assistance with setting-up the metrology hardware
- Assistance with the setting of the reference network. It is important to mention that the users will be taught how to locate an instrument and the importance of a reference network. They will however, not receive assistance with setting up a reference network. Further details on this is provided in the description of the experiments.
- Monitoring of the environmental conditions of the assembly and inspection area
- Projection of the measurement results on the actual component

These four aspects were considered as non-critical for satisfactorily answering the 4 research questions. It was then possible to design the experiment that aimed at testing an ISLVM implementation prototype and which are defined below.

Questions 1 and 2 are based on a comparison between the proposed ISLVM prototype and current procedures (i.e. paper and digital manuals). The use of large volume metrology instruments, such as laser trackers, and the expertise required to effectively use them for maximum benefit is regarded as a specialist task. Training courses offered by third party companies are costly and aimed at high level use only. Due to the complexity of using LVM instruments, user manuals will typically only provide basic information on how to initially set up an instrument. Manuals often do not provide information on best practices and measurement considerations. For this reason, it can be challenging for an operator to gain an understanding of metrology best practice. Commonly seen within the industrial sector, manuals and procedures are created internally following training as a means for ensuring measurement standardisation. Manuals can be either printed or accessed in digital form to guide operators through an official process. For this reason, within the proposed experimental tests, two guides have been designed for comparison with the ISLVM prototype. The first is a printed guide, the second is a digital guide. Both guides contain detailed images and descriptions of the processes.

The experimental test consisted of identifying suitable volunteers who have no or very little experience in metrology, have never used SA, or a laser tracker to measure specific locations of an assembly. The same set of volunteers will follow the guidance for each of the 3 different test interfaces (paper manual, laptop manual, and MR guidance). Through carrying out these tests the volunteer will gain an understanding of how a laser tracker works, be able to locate this instrument in the 3D CAD volume, take 8 designated measurements of an assembly, and finally produce a report in SA that shows the results of the inspection process. This experiment was devised due to the following:

- It is a task that can be performed safely by a single operator whilst wearing a MR device.
- The degree of difficulty of the task is sufficient, such that inexperienced users could not complete this task without any previous training or a step-by-step guidance taking them through the process.

The experimental test set-up environment, as shown in Figure 27, consists of a desk on which the laptop was placed. When the paper manual was used, it was placed on the desk beside the laptop for the users to follow. In front of the desk is a digital display. This screen was connected to the laptop to function as an extra monitor in which outputs from SA were being displayed. To the left of the desk and the screen was a 100cmx60cmx16cm granite table where the assembly was placed. The assembly was constructed from 4 Witte reconfigurable fixtures (Witte, 2017). This type of modular tooling is used in industry to build fixtures, some examples include holding fixtures, measuring fixtures or jigs, checking gauges, gap and flush gauges, match metal fixtures, tool reference models, and data control models. The dimensions and accuracy of various types of profile enable rigid configurations in any type and dimension. Ten 0.5” inch fixed installation SMRs (Hexagon, 2017) were glued to the frame supporting the granite table. These SMRs constitute the reference network that was used to locate the laser tracker in the 3D CAD volume.

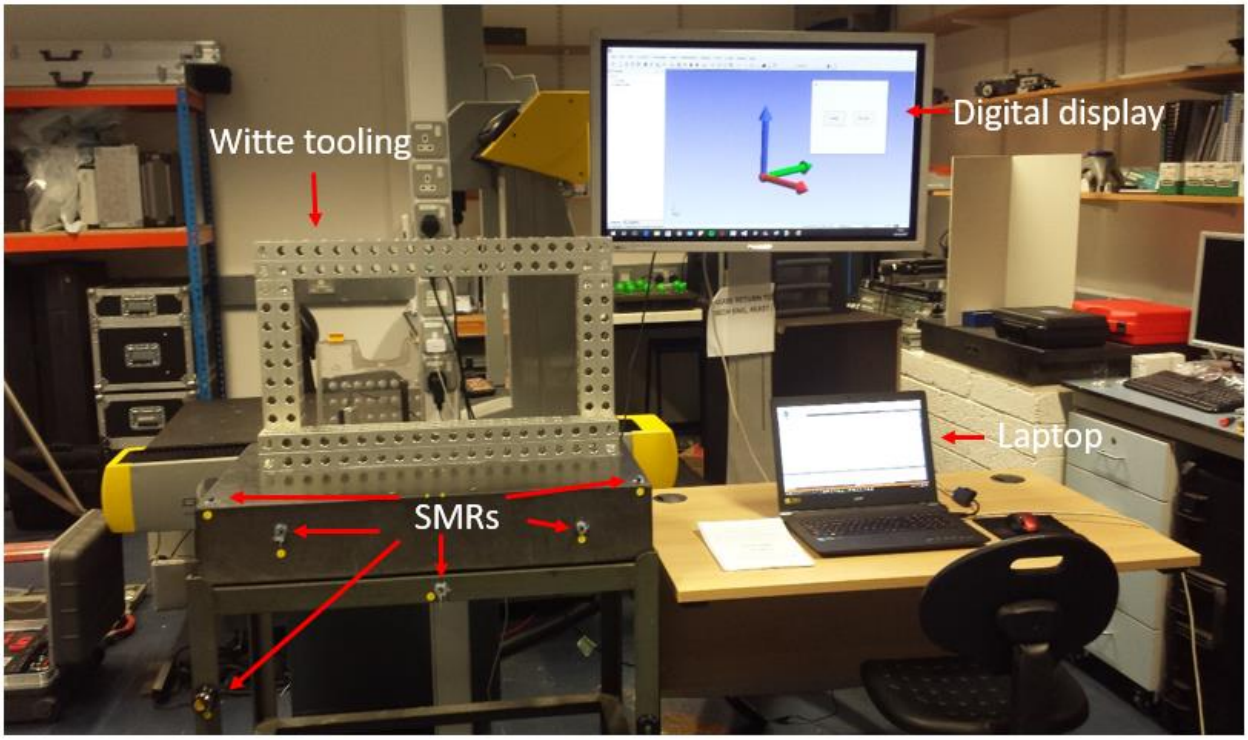


Figure 27 - Set up for the ISLVM experiment.

5.6 Participant Selection

There was a total of 72 volunteers that took part in the test. The reason for this is that there were 6 different orders in which the test could be completed, and a group of 12 participants would perform each order to statistically counter-balance the study. This is further detailed in Section 5.7. The 72 participants that took part in the study were not paid, and they were selected from a wide ranging background. Their background, gender, nationality, level of education or profession were not taken into account. The only requirements to fulfil were the following:

- Above 18 years old.
- Fluent English speakers.
- No previous experience with a laser tracker and preferably no experience with metrology.

There were 3 reasons why non-experts were selected to participate in the experimental tests:

i. Choosing participants with no metrology experience is in-line with the focus of this study, which is inexperienced operators performing an inspection process to assess their performance. A previous study from (Syberfeldt, Danielsson and Holm, 2015) applied the same approach to their AR assembly guidance research.
ii. By having inexperienced users undertake the tests, it is possible to minimize bias towards a population with expertise in assembly or inspection, and thus not fully evaluate the actual performance of the ISLVM prototype. This strategy was used by (Tang *et al.*, 2003) when they used Duplo blocks (LEGO, 2017) to minimize the bias towards a population with expertise in assembly tasks for their AR assembly guidance system. Thus, the results could be generalised for trained users.
iii. The use of non-expert subjects for the testing of AR assembly applications has been implemented by seven research projects from (Tang *et al.*, 2003; Hou *et al.*, 2013; Khuong *et al.*, 2014; Odenthal *et al.*, 2014; Re and Bordegoni, 2014; Radkowski, Herrema and Oliver, 2015; Syberfeldt, Danielsson and Holm, 2015). Hence, following practice implemented in the literature it was determined that non-expert participants should be used to test the ISLVM prototype.

5.7 Performance of Tests

The procedure for the experimental tests for each of the 72 participants in the study was as follows:

I. Upon arrival each participant was asked to read and sign a consent form stating their anonymity and that they agreed that the data gathered from their participation could be published.
II. Participants were then asked the following questions:
    1. Age
    2. Gender
    3. Profession
    4. Level of education
    5. Level of English proficiency (native or non-native)

    This question was asked because the HoloLens can work with voice commands. Hence, it was determined to check if the accent of the user had any impact on the performance of the HoloLens voice recognition software.

    6. Are you colour blind?

    Holograms projected through the HoloLens were in colour. In case the person was colour blind, it would be important to see if this had an impact on their performance through the inspection process.

    7. Have you experienced health-related problems when using electronic information displays (i.e. tablets, phones, laptops, AR, VR)?

    In case a participant would answer yes to this question, they would be asked what has been their experience and a decision would be made if they would do the test or not.

    8. How often do you use a computer?

    This question was asked to determine how comfortable the user was using a computer and a digital interface.

    9. Do you play video games?
    10. If you do play video games, how often do you play them?

    These two questions were asked to see if there could be a correlation between people who often play video games and their performance and opinion of the MR device.

    11. Have you had any previous experience with virtual reality?
    12. Have you had any previous experience with augmented reality?
    13. Have you had any previous experience with using metrology instruments or software?

It was important to know if the user had any previous experience with a laser tracker or the use of SA, as the experiment was designed for people with no experience in these processes, in particular, the laser tracker. If the user replied that they had previously used a laser tracker then they would not be allowed to perform the test and not be counted as a volunteer for the experiment.

III. After the questionnaire, a brief introduction on AR and MR was given to each participant. They then receive a short description of the activities, equipment that requires careful and safe operation, and finally they were given an opportunity to ask questions.

IV. As previously mentioned in the test definition Section 5.5 there are 3 different tests that the same volunteer will be doing. Test 1: following a paper manual, test 2: using a computer based digital manual, and test 3: using the HoloLens. Since the test subject would be performing the same test but with different interfaces, it was recognized that there would be a carry on effect, and that the experience gained by the user during the first experiment could affect the results of the second and third tests. In order to counter balance this carry on effect, and reduce the likelihood of obtaining false results, a counterbalanced experimental design (Shuttleworth, 2017) was implemented. Different combinations of orders of the 3 tests were identified. These were a total of 6 different combinations of orders in which the 3 interfaces could be used. Thus, a group of 12 volunteers would perform one of these 6 orders, then another group of 12 volunteers would perform a different order. This method would be repeated until 6 different groups of 12 volunteers had completed the 6 different combinations of orders. During the introduction the volunteers were told in which order they would be performing the tests. The 6 different orders in which the experiments were performed is as follows:

  - Paper Manual (PM), Laptop Interface (LI), Mixed Reality Interface (MRI)
  - PM, MRI, LI
  - LI, PM, MRI
  - LI, MRI, PM
  - MRI, PM, LI
  - MRI, LI, PM

V. Once the introduction was finished and the volunteer had no further questions, they proceeded to carry out the tests. The actions performed with each of the interfaces were the following:

- Test 1, Paper Manual: For the paper based manual test the volunteer used a printout guide (Appendix C) to follow the script that was developed in Section 5.4. This code automates steps that would need to be performed in SA to complete the inspection process. The volunteer, at this point still needs to perform tasks and interact with SA. These steps were automated to reduce time. It would take considerable time for a new user to learn and perform these steps, and is not needed to answer the research questions. Test 1 begins with a brief explanation on the importance of metrology. Then the user is introduced to SA and asked to start the script by pushing a button that was displayed on the digital display. The set-up of the experiment in SA and the initialization of the laser tracker takes approximately 2 minutes to initialise. During this time the volunteer is asked to continue reading the manual where they find an explanation of why there is a need to locate an instrument within the 3D CAD space of SA. The manual then guides the participant through a step-by-step procedure on how to do this. Once the instrument location procedure is finished, the user then measures 8 points on the assembly. Again, the manual takes them through this process with detailed explanation and figures. Figure 28 provides an example of one of the figures used to indicate a measurement point on the assembly.

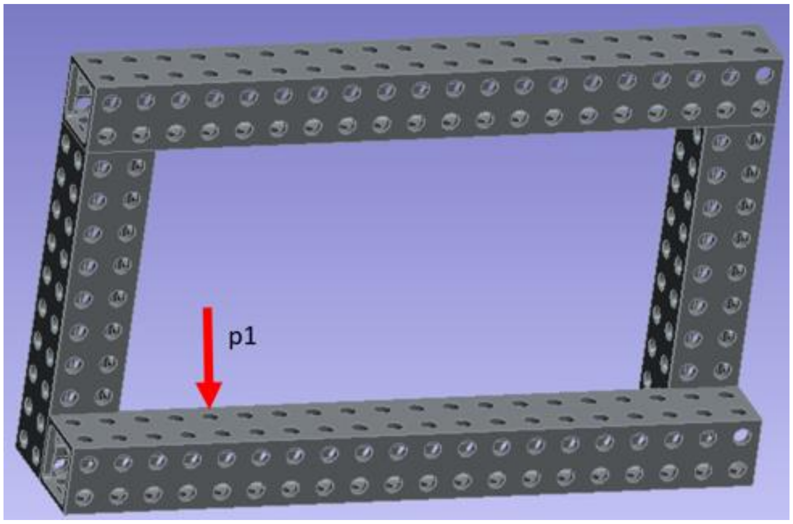
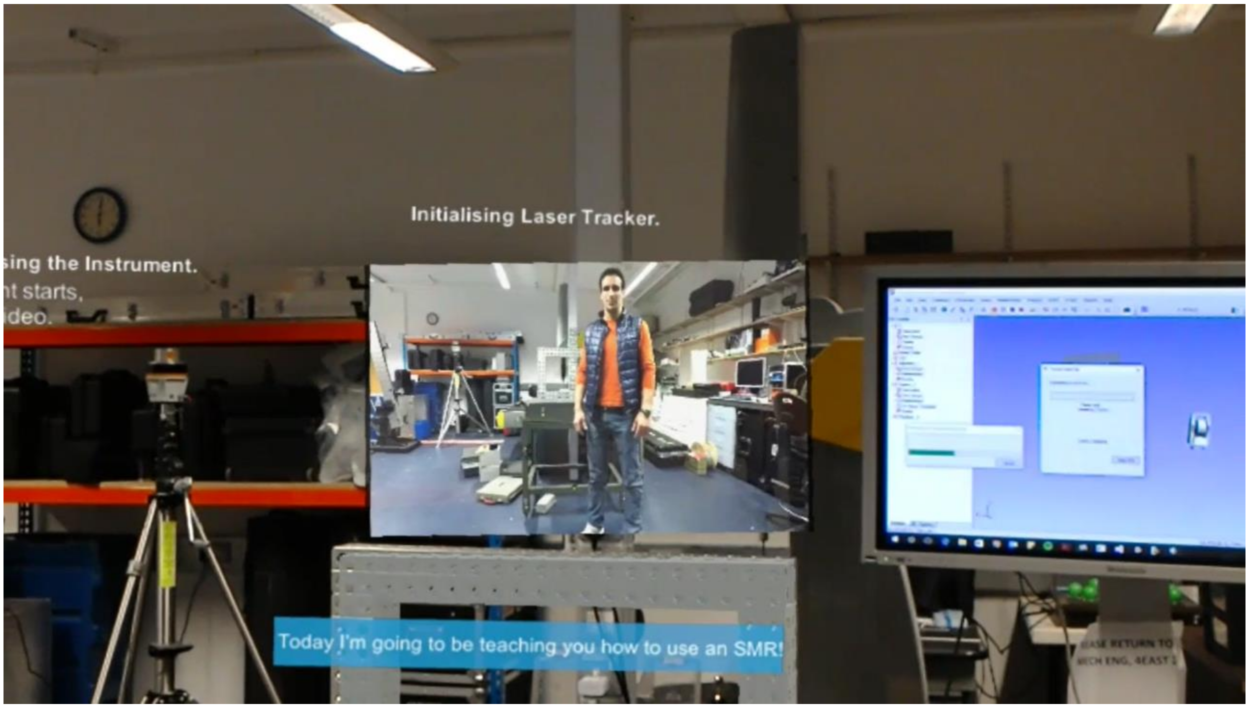


Figure 28 - Example of an image used to guide the volunteer through the measurement process.

After the measurements have been completed the script automatically creates a relationship between the measured points and the nominal data, then performs a best fit between the two data sets, calculates the deviations and finally creates a report in which it shows these deviations. At this point the volunteer can view the accuracy of their measurements.

- Test 2, Digital Manual: This test is the same as Test 1, using the same information and script to guide the volunteers through the inspection process. The two main differences between Test 1 and Test 2 are that videos are used to explain different aspects of the process instead of just text, thus presenting the information in two different ways and altering the learning process. The second difference is in how the user interacts with the digital manual while they take the measurements is inherently different from a paper manual, which could potentially cause more errors. There are 3 videos included in Test 2. The first one explains and demonstrates an SMR and how it is used. The second video explains the need to locate an instrument within a 3D CAD space. The third video is used to prompt the user to take the SMR once the location of the instrument has finished and proceed to take the 8 assembly measurements. This guide can be found in Appendix D.

- Test 3, MR Interface: The test with the HoloLens covered the same material as Tests 1 and 2. However, it is inherently different from the first two tests because the volunteers had their hands free at all times, interacting with the HoloLens through voice commands. The only interaction with the laptop was a section of the test that required the use of a mouse to click on certain commands in SA, which were not accessible through their SDK and could not be programmed for interaction with voice commands. The test begins by providing the same brief explanation on metrology as in Test 1 and 2, followed by an introduction to SA. These explanations were given through a voice recording that played on the HoloLens with the user also able to see the subtitles displayed in front of them through the headset. They would begin and continue through each step by giving appropriate voice commands that were displayed in front of them. Once the introduction and first explanations were finished the user was prompted to start the inspection process by giving a voice command that imports the same project settings into SA as the previous tests. Then the user would add and initialize a laser tracker to the project environment in SA through a voice command. While the laser tracker initialises, the same video explaining how to use an SMR that was used in the test 2 experiment was displayed through the HoloLens. The video is displayed directly on top of the assembly within the augmented environment. Figure 29, below, shows the placement of the video above the actual assembly.



Today I'm going to be teaching you how to use an SMR!

Figure 29 – First video in the MR interface

As the first video finishes, the user is requested to give another voice command and the second video explaining the importance of instrument location and how to do it is displayed on the left side of the assembly. Figure 30 shows how this video looked through the HoloLens.

SA has no idea of where the Laser Tracker is relative to our assembly object, nor our reference network.

Figure 30 – Second video from the volunteer's perspective.

Once this video finishes the volunteer was taken through a step by step process using holograms on how to locate the laser tracker in the 3D CAD space in SA. When the volunteer finished this step the third video prompting them to take the SMR and perform the 8 measurements on the assembly was displayed. The volunteer would then be told where to measure with holograms displayed on the assembly. The user would take a measurement using a voice command. Figure 31 shows how the measurement guidance appeared through the HoloLens.

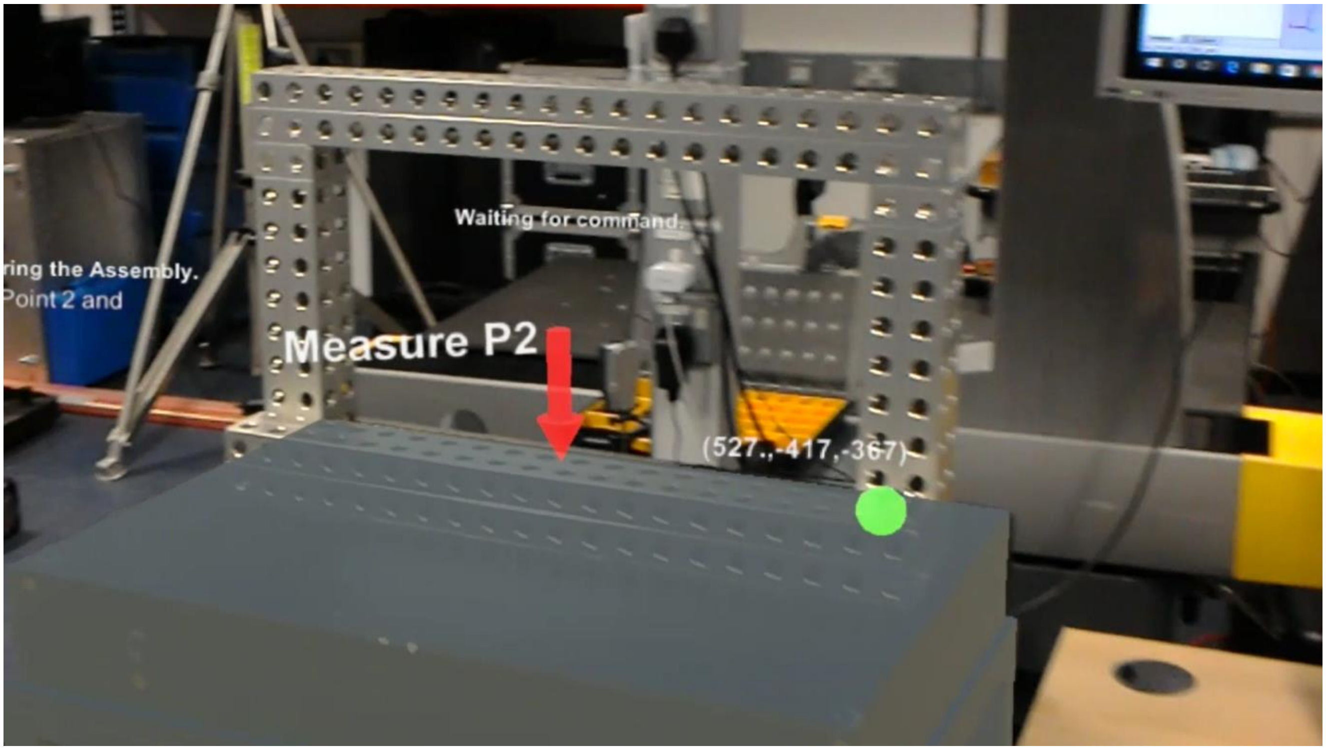


Figure 31 - Measurement guidance looked through the HoloLens.

Once the measurement process had finished, the participant would give voice commands to create relationships, perform a best fit, calculate the deviations and generate a report. Whilst this was being undertaken, further explanations of each step is provided through voice recordings.

VI. After each test (1-3) was completed each participant was asked to complete a short questionnaire to capture effectiveness and usability data, as explained below in Section 5.8.

5.8 Data Capture

As mentioned in the literature review (Hou and Wang, 2013), the proposed evaluation of AR applications can be divided into two types, namely effectiveness evaluation and usability evaluation. Effectiveness evaluates the capability of the system to deliver the desired result for a certain task, while usability evaluates the ease of use, comfort, and learnability of the AR system. Almost all the user case studies that compared an AR system with other conventional methods used these two categories to evaluate the results. This approach has also been used for this research. In particular, 5 studies (Tang *et al.*, 2003; Gavish *et al.*, 2013; Khuong *et al.*, 2014; Radkowski, Herrema and Oliver, 2015; Syberfeldt, Danielsson and Holm, 2015) were used as a guideline to determine the effectiveness variables and help design the questionnaire that was given to the participants to answer after they had completed the experiment with each of the interfaces. It is of the author's opinion that in order to determine if an ISLVM has the potential to outperform the current practices, both of these evaluations need to be given the same importance. The reason why the usability evaluation should be considered as being as important as the effectiveness variables is because research has shown that happiness leads to a 12% increase in productivity, while unhappy workers have been proven to be 10% less productive (Oswald, Proto and Sgroi, 2015). Where, happiness is defined as a state of well-being and contentment, as well as a pleasurable or satisfying experience (Merriam-Webster, 2017). While, unhappiness is defined as the feeling of not being satisfied or pleased with a situation (Oxford Dictionaries, 2017). Therefore, it is important to keep track of the mood and general feeling of the user during the study. Furthermore, even if the ISLVM proves to be more accurate and produce less errors, if the operators do not feel comfortable and do not enjoy the experience there is a higher probability of the ISLVM not being used.

The effectiveness variables captured:

- **Completion time of the inspection process.** The time taken was from the moment the participant started reading the first sentence, or gave the first voice command to when they finished reading or performed the last task of the experiment.
- **Number of errors made.** An error was counted if the volunteer measured a point in an incorrect position or if they took more than 8 points of the assembly.
- **If it was a successful completion of the experiment or not.** This refers to not only completing all process steps, but to obtaining useful information for an inspection process. This means that if the points taken were not on the assembly, resulting in the best-fit misaligning the CAD model to the reference network, it would be considered as an unsuccessful completion of the inspection task.

The usability questionnaire that was given to the volunteers after each experiment was the following:

1. I found the _________ interface easy to understand.
2. I found it easy to use the _____ interface to perform the verifications needed.
3. I felt that I performed quickly with the _____ interface.
4. If I had to conduct measurements on a regular basis, the _______ interface is a technique I would appreciate having available.
5. I found the ______ interface physically demanding.
6. I found the ______ interface mentally demanding.
7. I found the _______ interface frustrating to use.
8. Did you have fun?
9. Can you remember why we need to locate an instrument?
   a) So SA knows that the points belong to the assembly.
   b) The Laser Tracker has been misplaced.
   c) To tell SA where the Laser Tracker is relative to the assembly, and reference network.
   d) To be able to do a Best-Fit afterwards.
10. If you could choose which interface you could work with on a regular basis, which one would it be?
    a) Paper based Interface
    b) Laptop/Computer Interface
    c) Mixed Reality Interface
    ** For this last question the volunteers were asked not answer it until they had completed all of the 3 experiments with the 3 interfaces. Once this was achieved they were asked to answer this question.*

The first 8 questions were answered by selecting a value from a 3 value Likert scale, where 1 was “Totally Disagree” and 3 was “Totally Agree”. This scale was determined after the questionnaire was given to research colleagues, and a discussion around varied opinions that having a large Likert scale can be difficult to evaluate as it gives room to a wider perception, which can vary greatly from person to person was had. After these discussions it was determined that having only 3 options forces a person to make more concrete decisions and say “yes I do agree”, “no I do not agree”, or “I’m somewhere in between”.

5.9 Data Analysis of the Experimental Test

There are three effectiveness variables gathered during the tests. Each is analysed differently. The methods used for each variable are the following:

1. **Completion Time of the inspection process:** This variable will not be statistically analysed as there is a significant difference between the test interfaces. Both the laptop (Test 2) and the mixed reality interface (Test 3) have two videos, which the paper manual (Test 3) does not have. Furthermore, the MR interface has audio that neither of the other two interfaces have, and it does not allow the user to skip steps. Hence, they are obliged to wait and see both videos, or hear the audios even though they might already know the content (in case the MR interface was the second or third in the order in which the tests were performed). This was not the case in the digital interface, as the manual guide was done through a Power Point presentation and the user was allowed to move freely back and forth through the instructions. This presents a significant difference in the three interfaces that results in it being meaningless to perform a statistical analysis on the time results. Therefore, this data will be only used as a descriptive measure for each test.
2. **Number of errors made:** In 2014, Khuong et al. (2014) performed a participant based study to evaluate the effectiveness and usability of an AR system to aid in an assembly exercise. In their study, 24 participants were subjected to 4 different experimental conditions. This approach has been undertaken in this research, with the exception that this research has 3 different experimental conditions and not 4. Khuong et al. (2014) statistically analysed the number of errors by performing a repeated measures ANOVA to determine if there was any statistically significant difference between the four interfaces. Although a repeated measures ANOVA is an ideal method to analyse an experiment in which an individual is subject to all of the different experimental conditions, it was decided not to use this method for this research. The reason being that in order to conduct a repeated measures ANOVA the data set needs to fulfil 5 assumptions. The data set for these experiments clearly violates one of these assumptions and has an increased probability of violating a second assumption. The first assumption violated is that in order to conduct a repeated measures ANOVA, the dependant variable (i.e. number of errors) should be a continuous variable. The variable type for number of errors is a discrete data variable, and does not fulfil this assumption. The second assumption violated is that the data needs to be normally distributed. Due to the nature of the generated data (0, 1, 2, 3 …) there is an increased probability of the result not being normally distributed. If this is the case then this second assumption would not be fulfilled and it would not be

adequate to perform a repeated measures ANOVA to analyse the data set obtained. In order to account for these two scenarios, a Generalized Linear Mixed Model (GLMM) with a Poisson distribution method is used. A GLMM allows a data set to be discrete, for it to be non-normal, and as it is a “mixed” model it accounts for a repeated measures design to be used. Therefore, it was determined that this would be a robust method to use to analyse the number of errors obtained from each experimental conditions.

3. **If it was a successful completion or not:** The data gathered from this variable is not statistically analysed, due to it being considered subjective. This information will be presented as a success rate percentage. This data could support the results obtained from the analysis of the number of errors committed in each of the experimental test scenarios.

The usability questionnaire will have questions 1 through 8 statistically analysed. The method that will be used to perform the statistical analysis will be a Friedman Test. This method was selected due to it being a method used to analyse a group that has been tested three or more times, the group selected is a random sample from the population, the dependant variable needs to be measured at the ordinal or continuous level (where ordinal variables include Likert and other scales), and the samples obtained do not need to be normally distributed (Laerd Statistics, 2013). The data for these questions fulfil these requirements, thus it was selected as the method to statistically analyse the data gathered from questions 1-8. Questions 9 and 10 will be presented as percentages and will serve as supporting data to the rest of the research.

The data obtained from question 10 of the usability questionnaire will be compared against the number of errors made to observe if there is any relationship between the user’s preference on the interface and their actual performance.

5.10 Summary

This chapter presented the experimental work that was undertaken to test the ISLVM implementation prototype. Hardware selection is explained, the experimental tests are defined, participant selection is detailed, how tests are performed for each of the volunteers and what it was that each of the volunteers saw and experienced throughout the experimental conditions is captured. Then the data generated through the experiments is presented as well as how this information will be analysed and interpreted.

6. ISLVM Prototype Validation Results

6.1 Introduction

This chapter will present the results and findings of the analysis performed on the data gathered from the 72 volunteers that each completed the three different test conditions of a paper manual, a laptop interface, and an MR interface. These results will be analysed and discussed within the context of this research in Chapter 7.

6.2 Participant General Information

In Section 5.7 of Chapter 5, a general information questionnaire was presented. The data obtained from this questionnaire is presented, below:

1. **Age:**

   The age range of the 72 participants varied between a minimum of 19 through to a maximum of 52 years of age. The majority of volunteers were early to mid-twenties and early thirties. This resulted in an average age of the 72 volunteers being 26.8 years old.

2. **Gender:**

   From the start of the participant recruitment, it was intended to have a gender balanced spread of participants. The final numbers consisted of 42 male participants (58%), and 30 female participants (42%).

3. **Profession:**

   Out of the 72 volunteers only 16 were non-students. The remaining volunteers (56) were studying fulltime undergraduate, Masters, or PhD programmes. It is important to mention that the volunteers came from a wide range of areas and disciplines within the University of Bath (UoB). These ranged from the departments of Psychology, Chemistry, Mechanical Engineering, IT support, Accounting and Finance, Studio Engineer, Centre Coordinator, and one Trusts and Foundations Manager.

4. Level of education:

Due to the volunteers being selected from the UoB the lowest level of education were the participants who had just started studying their undergraduate degree. The most qualified volunteers had a PhD (13 had completed a PhD).

5. Are you a native English speaker?

Due to the potential for different accents having an impact on the detection of the voice commands, a spread as diverse as possible was sought. 51 volunteers were native English speakers and 21 were non-native English speakers resulting in the following distribution:

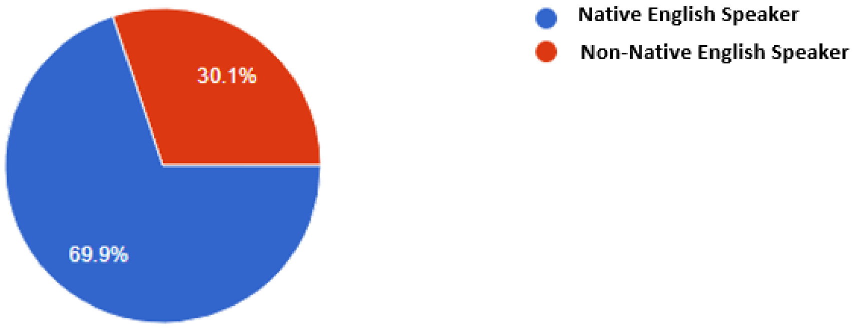


Figure 32 - Distribution of Native English speakers vs Non-Native English speakers

6. Are you colour blind?

Out of the 72 volunteers only one volunteer mentioned having a slight issue with colour detection, but once the experiment was explained the volunteer said there would be no adverse issues and that the colours that were going to be displayed throughout the 3 tests could be detected.

7. Have you had any health related problems in the past with using electronic information displays (i.e. tablets, phones, laptops, AR, VR)?

None of the participants in the experiments had any health related problems with using information displays.

8. How often do you use a computer?

The 72 volunteers used a computer daily, which meant that there were no issues with computer illiteracy.

9. Do you play video games?

Out of the 72 volunteers, 35 (48%) do play video games.

10. If you do play video games, how often do you play them?

From that 48% of participants that do play video games below is a pie chart describing how often they play video games:

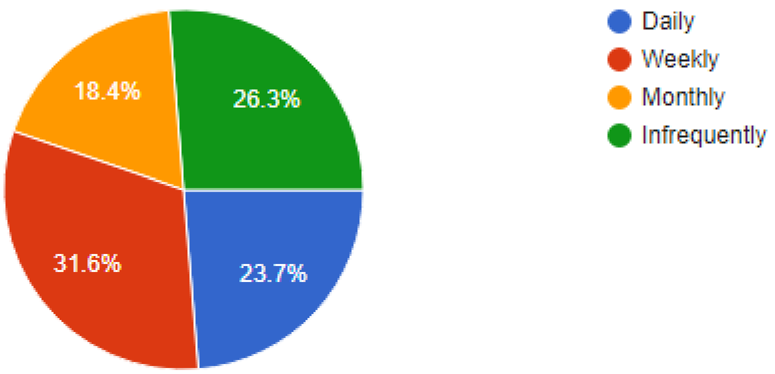


Figure 33 - Distribution of video game playing frequency

Infrequently represents somebody who would play video games less than once a month.

11. Have you had any previous experience with Virtual Reality?

From the 72 volunteers only 25 (35%) had previously used some type of Virtual Reality interface. These ranged from Google Cardboard (Google, 2017) to one of the HTC Vive (Vive, 2017) or Oculus Rift (Oculus, 2017) models.

12. Have you had any previous experience with Augmented Reality?

Out of the 72 volunteers, only 15 (20%) had previously used an AR interface. Only two had previously used a HoloLens (which they had only played games on), and the rest had mainly used AR on their phones for a game or a certain marketing application.

13. Have you had any previous experience with metrology instruments or software?

From the participants selected, only nine had previous experience using a metrology instrument or software. However, it is important to mention that they had only used a scanner, a theodolite, a

CMM, or a portable CMM but none of the participants had ever used a laser tracker or SpatialAnalyzer (SA) before.

6.3 Results from the Effectiveness Variables

The three effectiveness variables that were gathered during the experiments were: i) the time taken to complete the activity with each of the three different interfaces, ii) the number of errors committed with each interface, and iii) was it a successful completion of the inspection or not. The data gathered from the experiments for each of these variables will be presented below:

i) Time taken to complete the activity:

As mentioned in section 5.8 this variable will not be statistically analysed due to the innate differences in the design of the interfaces. However, what is presented is a simple comparison of the times it took the volunteers when they used a particular interface (test 1-3) for the first time. Due to the different order combinations, there were a total of 24 times that each test was done for the first time without previously doing either of the other 2 tests. These times are compared in Figure 34.

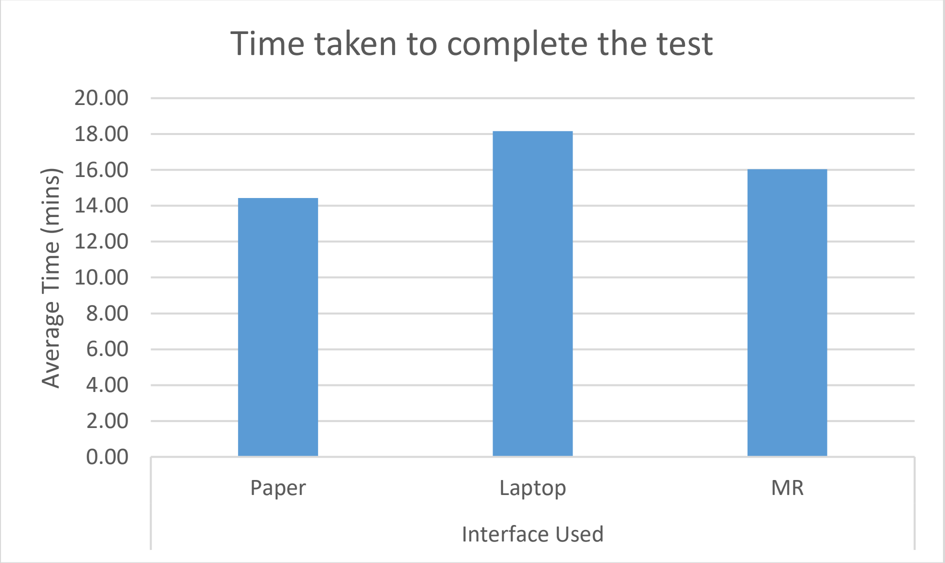


Figure 34 - Distribution of average time taken to complete the first exercise with each interface

As observed in Figure 34 the test with the fastest average time to completion was the paper manual, which was to be expected as this interface did not have any videos or audio which the volunteer was obliged to listen to or observe. However, it is interesting to see that despite having only two videos (which were the same videos displayed in MR) and no audio, the laptop test resulted in the longest completion time.

ii) Number of errors committed in each test:

As explained in Section 5.9, the data set obtained from the number of errors committed from each volunteer with each test violates at least one of the five assumptions and potentially two of these assumptions is required to conduct a repeated measures ANOVA which were the following:

1. The dependent variable to be analysed needs to be measured at the continuous level. The data obtained from number of errors is a discrete variable type, which therefore violates this assumption.
2. The distribution of the data set obtained needs to be approximately normally distributed. The way to verify this is by conducting a Shapiro-Wilk test. This method was chosen due to the Shapiro-Wil test being more appropriate for small sample sizes, typically less than 50. However, it can still handle sample sizes as big as 2000. As the sample size is 72, this method was deemed to be appropriate. If the significance value is above 0.05 then the data is normal, and if the value is below 0.05 then the data significantly deviates from a normal distribution. The result from this can be seen in Table 2.

Since the significance value for all 3 interfaces is 0, it can be said that the data from all 3 interfaces significantly deviates from a normal distribution, therefore this assumption is also violated.

Table 2 - Shapiro-Wilk test for normality.

Shapiro-Wilk Test of Normality		
Test	**df**	**Significance value**
Paper	72	.000
Laptop	72	.000
MR	72	.000

As 2 of the 5 assumptions needed to run a repeated measures ANOVA have been violated the results obtained from this model are not reliable. Therefore, this method will not be used and the data will be analysed using a GLMM (Generalized Linear Mixed Model) method with a Poisson distribution, and solved with a Bayesian approach (the model used in R can be found in Appendix E).

This method modelled the distributions of the errors given, regardless of which test was performed and without taking into account the order. The reason behind this is that all orders were taken into account and an equal set of tests were conducted for the 6 different combinations as explained in Section 5.7. There should be no effect from the order in which the interfaces were used in the final results as the order sets were counterbalanced.

The output obtained from solving this model with a Bayesian approach is a 95% confidence interval of the error rate of each of the interfaces used. The confidence interval is composed of a mean, a lower boundary (LB), and an upper boundary (UB). The results obtained from this model can be seen in Table 3.

Table 3 - Confidence intervals obtained from solving a GLMM with a Poisson distribution

Test	Mean	LB	UB
Paper	0.44	0.41	0.49
Laptop	0.80	0.76	0.88
MR	0.23	0.22	0.26

To determine if there is a statistically significant difference between the interfaces, the confidence intervals need to be compared to one another. If the intervals overlap, there is no evidence of a significant difference. However, if they do not overlap then it can be concluded that there is a statistically significant difference between those interfaces. Figure 35 is a graphical representation of Table 3, which helps interpret the data and establish if there has been a significant difference between the 3 tests or not.

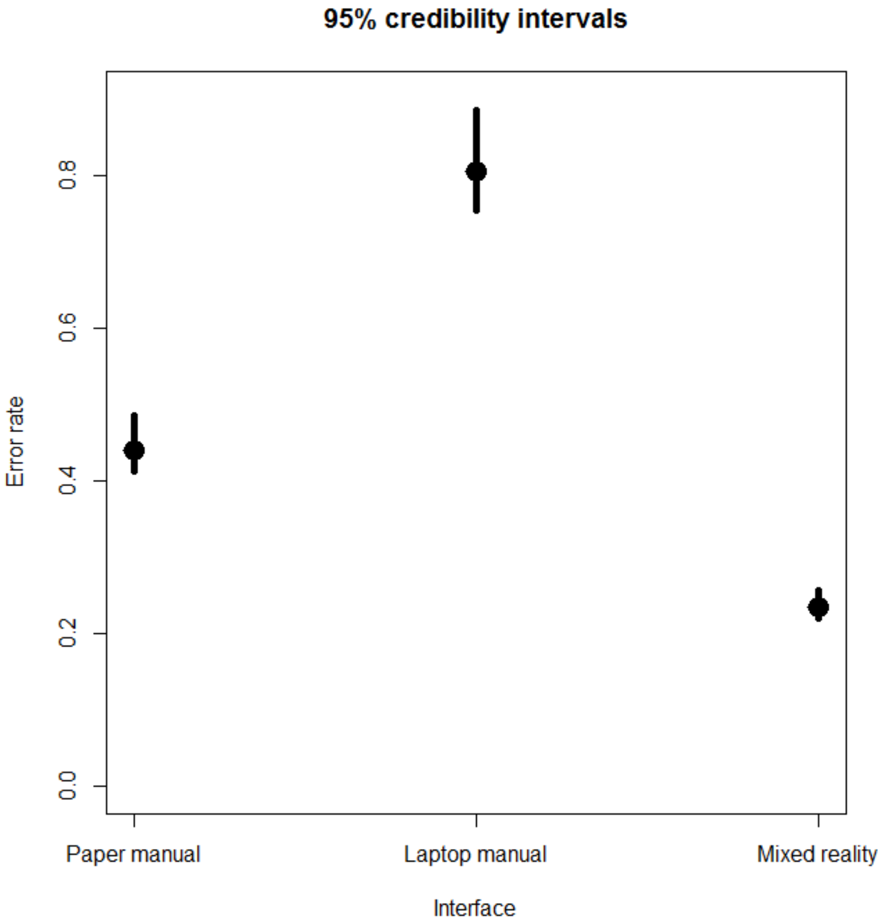


Figure 35 - Confidence intervals obtained from the GLMM.

Figure 35 can be interpreted as follows:

- None of the confidence intervals of the tests overlap, therefore there is a significant statistical difference between the 3 interfaces.
- The interface that resulted in the least amount of errors was MR (Test 3), followed by the paper interface (Test 1), and the interface with the highest number of errors and variation was the laptop (Test 2).
- The interface with the least amount of variation is MR (Test 3) which has the smallest confidence interval.

In order to observe the spread of the results obtained, a boxplot has been created with the median values of the number of errors committed in each test**.** The median is represented by the black circle, and its value can be seen beside it. The median would typically be in the middle of the boxplot. However, this is not the case for any of the three tests, suggesting that the data is non-normal. It is important to mention that there is no box for the MR interface (test 3), and the median value is at zero. This is due to the data being at zero except for 12 instances that can be seen by the outliers represented by empty diamonds, representing less than 25% of the data. The paper interface (Test 1) also has a median value of zero. However, it had at least 25% of the volunteers committing one error, seven committing 2 errors and only one volunteer committing three errors. The laptop interface (Test 2) presented a median value of 1, which means that 50% of the volunteers using this interface committed zero or one error, six committing two errors, and five committing 3 errors. The mean value of each test can be seen by the empty circles with a cross inside them. This boxplot can be seen in Figure 36.

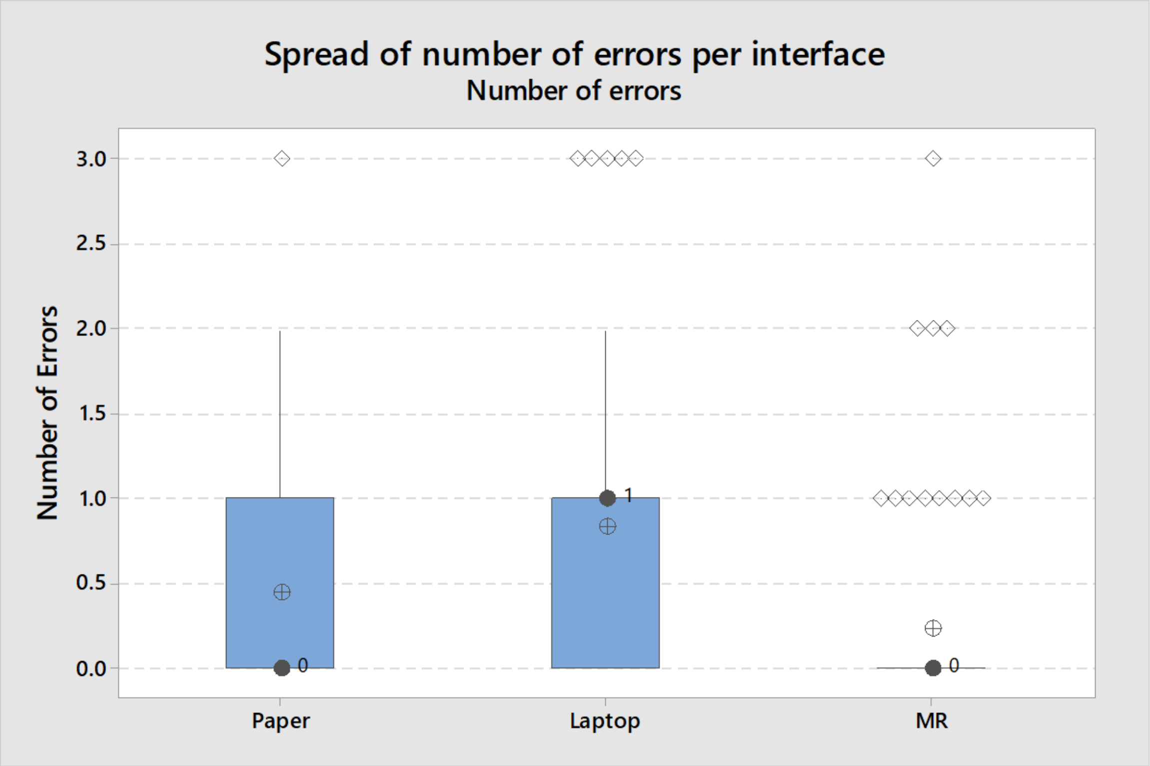


Figure 36 - The number of errors for each interface.

iii) If it was a successful completion or not:

As explained in Section 5.9, this variable will not be statistically analysed. The results obtained show that the highest success rate was obtained by the MR interface (Test 3) with a 94% success rate, followed by the paper manual (Test 1) with a 71% success rate, and finally with the laptop interface (Test 2) which had a 53% success rate. This can be seen in

Table 4.

Table 4 - Success rate for successful completions for each interface.

Test	Interface	# of Successful Completions	# of Bad Completions	Success Rate %
1	**Paper Manual**	51	21	71
2	**Laptop**	38	34	53
3	**Mixed Reality**	68	4	94

As described in Section 5.8, a completion was considered successful when the user completed the exercise without committing any errors. A further criterion was that the points that they measured were still on the assembly being inspected, such that the best-fit would correctly align the measurements with the CAD model.

6.4 Results from the Usability Questionnaire

A questionnaire with 10 questions was given to the volunteers as soon as they completed each test. Questions 1-8 were statistically analysed using a Friedman Test in SPSS. However, the Friedman test only proves that there is an overall statistically significant difference between the mean ranks of the related groups, and it does not specify which groups in particular are different from each other in the event that a significant difference was found. In order to know the difference between groups it is necessary to conduct a post-hoc test called a Wilcoxon signed-rank test on the different combinations of the related groups. Once this test has been conducted it will be necessary to use a Bonferroni adjustment, due to the fact that multiple comparisons are being made (Laerd Statistics, 2013). The Bonferroni adjustment is obtained by taking the significance level that is currently being used (0.05) and dividing it by the number of different test that are being run. In this case it is 3, one for each of the three different tests. Hence, the new significant value that will be used to compare the results against is 0.017. Table 5 shows the median values, the results of the Friedman test and, in case there has been a significant statistical difference, the results from the Wilcoxon Signed Rank Test (WSRT) with the Bonferroni adjustment for questions 1 through 8. After this, the results for questions 9 and 10 will be presented as percentages and question 10 will compared to the performance of each volunteer to see if there is a correlation between their preferred test interface and their actual performance in number of errors with each test interface.

Table 5 - Median values, and results of the Friedman and Wilcoxon Signed Rank Test (WSRT) for questions 1 - 8.

	Interface	**Median**	**Friedman Test**				**WSRT p values (Bonferroni = 0.017)**					
			df	**Chi-Square**	**p Value**	**Stat. Sig? (Y/N)**	**P-MR**	**Stat. Sig?**	**L-MR**	**Stat. Sig?**	**L-P**	**Stat. Sig? (Y/N)**
Q1	**Paper**	3	2	2.198	.333	N	-	-	-	-	-	-
	Laptop	3										
	MR	3										
Q2	**Paper**	3	2	4.474	.107	N	-	-	-	-	-	-
	Laptop	3										
	MR	3										
Q3	**Paper**	2	2	5.822	.054	N	-	-	-	-	-	-
	Laptop	2										
	MR	3										
Q4	**Paper**	2	2	16.551	.000	Y	.000	Y	.000	Y	.784	N
	Laptop	2										
	MR	3										
Q5	**Paper**	1	2	19.414	.000	Y	.000	Y	.146	N	.011	Y
	Laptop	1										
	MR	2										
Q6	**Paper**	2	2	4.185	.123	N	-	-	-	-	-	-
	Laptop	2										
	MR	1										
Q7	**Paper**	1	2	.587	.746	N	-	-	-	-	-	-
	Laptop	1.5										
	MR	2										
Q8	**Paper**	2	2	70.640	.000	Y	.000	Y	.000	Y	.034	N
	Laptop	2										
	MR	3										

As can be seen from Table 5, only questions 4, 5, and 8 had a statistically significant difference. These questions are further analysed below:

4. If I had to conduct measurements on a regular basis, the _______ interface is a technique I would appreciate having available.

The results from the Friedman test in Table 5 demonstrate that there is a statistical significant difference between the preferred test interface being available to conduct measurements on a regular basis, χ2 (2) = 16.551, p = .000. From the results of the WSRT it can be seen that there was a statistically significant difference between the paper manual (Test 1) and the MR interface (Test 3) (p = .000), and between the laptop interface (Test 2) and the MR interface (Test 3) (p = 0.000). However, there was no significant differences between the laptop interface (Test 2) and the paper manual (Test 1) (p = 0.784). Figure 37 shows the distribution in a boxplot of the answers for each of the tests. This figure shows the difference in the median, and mean values between the MR interface (Test 3), and the paper manual (Test 1) and laptop interface (Test 2). It can be seen that the MR interface (Test 3) had 50% of the volunteers select "totally agree" (value #3) on using the interface on a regular basis. The paper manual (Test 1) and the laptop interface (Test 2) had 50% in the "not sure" region (value #2), and only 25% of the volunteers said that they would like to use it on a regular basis.

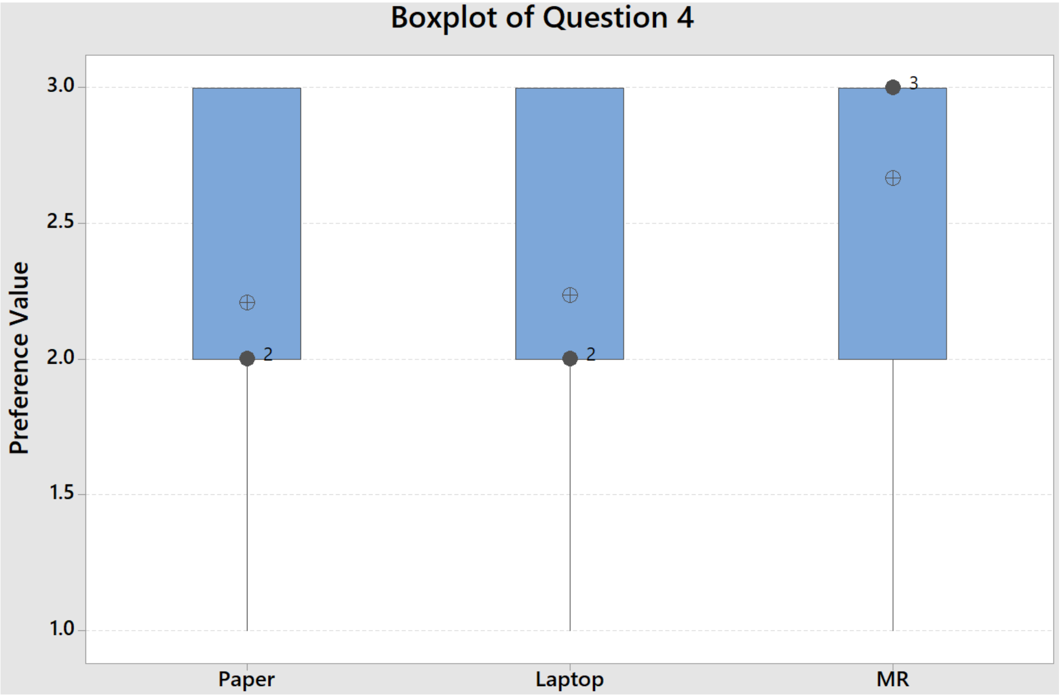


Figure 37 - The distribution of answers to question 4, (1 is totally disagree and 3 is totally agree).

5. I found the ______ interface physically demanding.

The results from the Friedman test in Table 5 demonstrate that there is a statistical significant difference in the perceived physical workload for each interface, χ2 (2) = 19.414, p = .000. From the results of the WSRT it can be seen that there was a statistically significant difference between the paper manual (Test 1) and the MR interface (Test 3) (p = .000), and between the laptop interface (Test 2) and the paper manual (test 1) (p = 0.011). However, there was no significant differences between the laptop (Test 2) and MR interface (Test 3) (p = 0.146). These differences can be seen in Figure 38 that shows the distribution of the volunteer's answers with boxplots for each test. It can be observed that for the paper manual (Test 1), 55 of the participants disagreed with the manual being physically demanding, 14 were indecisive, and only 3 volunteers thought it was physically demanding.

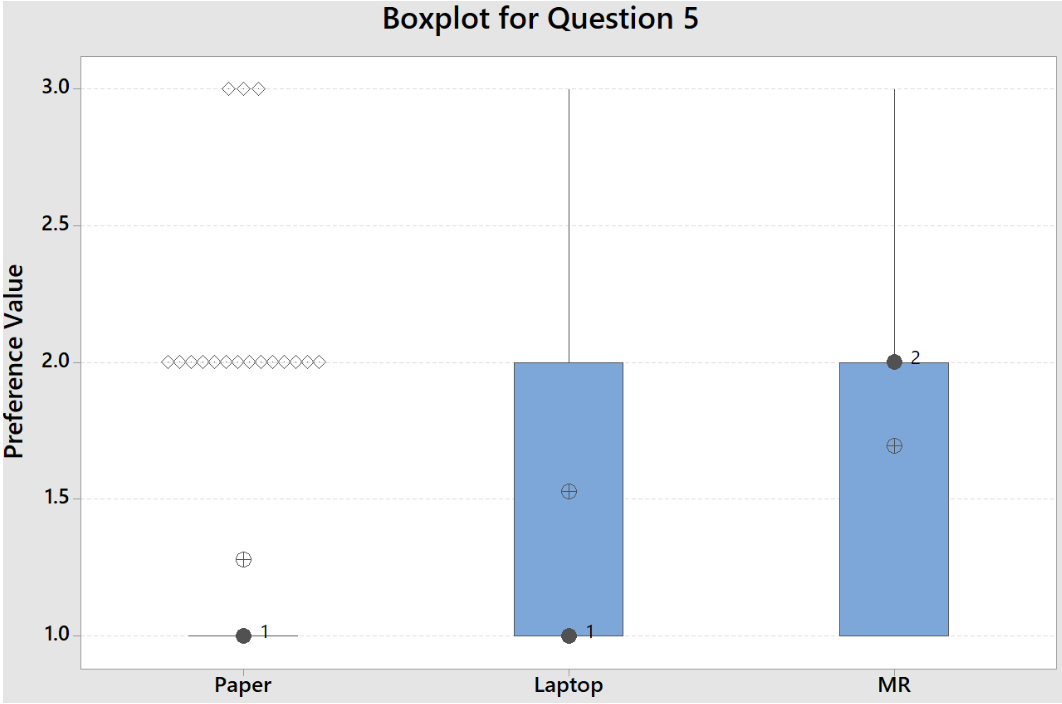


Figure 38 - The distribution of answers to question 5, (1 is totally disagree and 3 is totally agree).

8. Did you have fun?

The results from the Friedman test in Table 5 demonstrate that there is a statistical significant difference in the perceived amount of fun experienced using each interface, χ2 (2) = 70.640, p = .000. From the results of the WSRT it can be seen that there was a statistically significant difference between the paper manual (Test 1) and the MR interface (Test 3) (p = .000), and between the laptop interface (Test 2) and the MR interface (Test 3) (p = 0.000). However, there was no significant differences between the laptop interface (Test 2) and the paper manual (Test 1) (p = 0.034). It is important to mention that although 0.034 is indeed below 0.05 there is no statistical significance difference between these two interfaces due to the Bonferroni adjustment which lowers the p value to 0.017. These differences can be observed in Figure 39 where the boxplot shows that out of the 72 volunteers only 4 selected that they were indecisive of whether they had fun using the MR interface in test 3, while 68 of the volunteers “totally agreed” that they had fun using this interface.

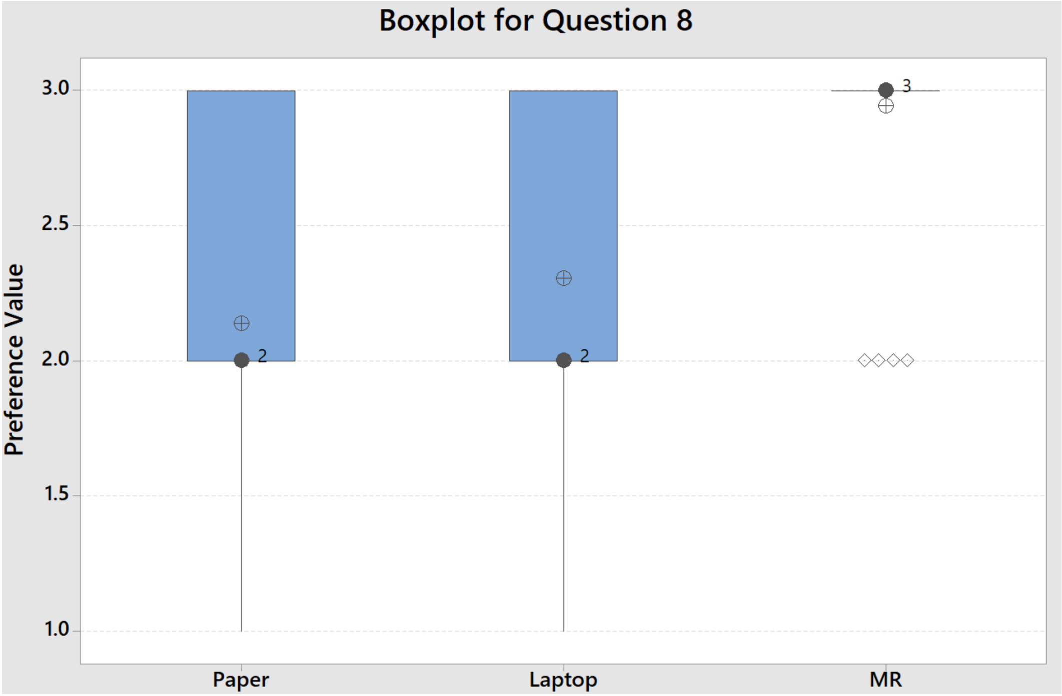


Figure 39 - The distribution of answers to question 8, (1 is totally disagree and 3 is totally agree).

9. Can you remember why we need to locate an instrument?

a) So SA knows that the points belong to the assembly.

b) The laser tracker has been misplaced.

c) To tell SA where the laser tracker is relative to the assembly, and reference network.

d) To be able to do a best-fit afterwards.

The volunteers were asked to answer this question after each test was completed. The correct answer was option "c". The results obtained from this question will be presented as a percentage of correct answers given by the volunteers for each test. These can be seen in Figure 40.

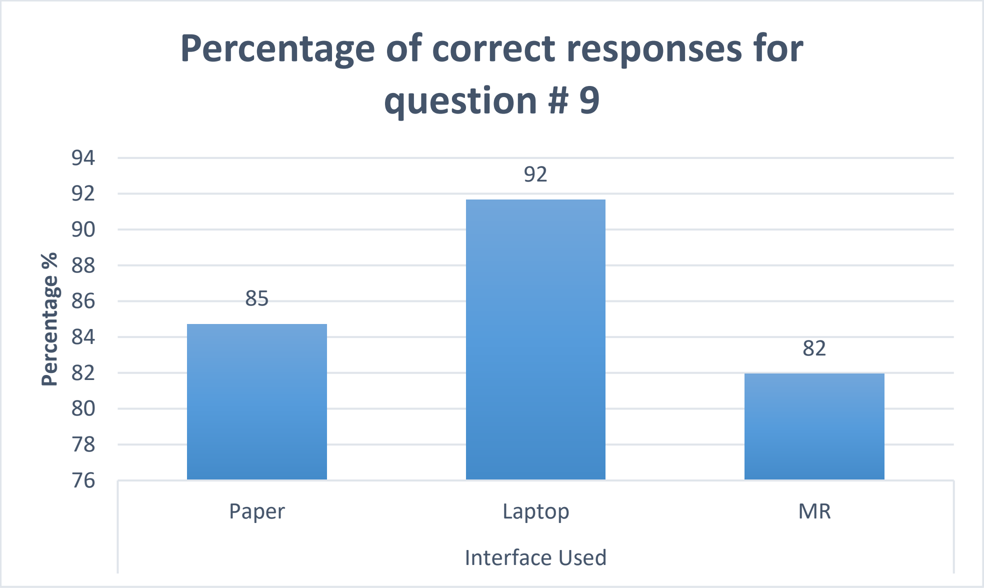


Figure 40 - Percentage of correct answers for each interface for question 9.

10. If you could choose which interface you could work with on a regular basis, which one would it be?

a) Paper based Interface

b) Laptop/Computer Interface

c) Mixed Reality Interface

This question was answered once by each volunteer at the end of the last test, which means that before they answered this question they had used all three interfaces (Test 1-3). The percentage of the preferred interface selected by the 72 volunteers can be seen in Figure 41. This data was further analysed and the preferred interface selected by the volunteer was compared to the number of errors that they had committed with each interface to see if the interface that they had selected had been the one with which they performed the best. If the selected interface had been the one with which they committed the least amount of errors or tied with another interface, it was considered that the volunteer had chosen the interface with which they had their best performance. However, if the interface that they chose had been the one with which they committed the most errors, or there was at least one other interface with which they committed less errors than their preferred selection, it was considered to be in disagreement with their preference. Figure 42 shows the results of this analysis in which 74% of the volunteers were in agreement with their preferred selection, while 26% of the volunteers chose the interface with which they performed worst. Furthermore, after analysing this data in detail, Table 6 shows the numbers for preferred interface versus best performance. Here, 1 is the paper manual, 2 is the laptop manual, and 3 is the MR interface. The numbers coloured in green represent the number of volunteers whose preference matched their best performance. The numbers in red represent volunteers whose preference did not match the interface with which they performed the best. The sum of the numbers in Table 6 equals 79 instead of 72. This is due to 7 volunteers having equal performance with two interfaces that they did not prefer. For example, if a volunteer preferred the laptop manual but they performed better, and equally well, with both the paper manual and the MR interface then both the paper manual and the MR interface were counted.

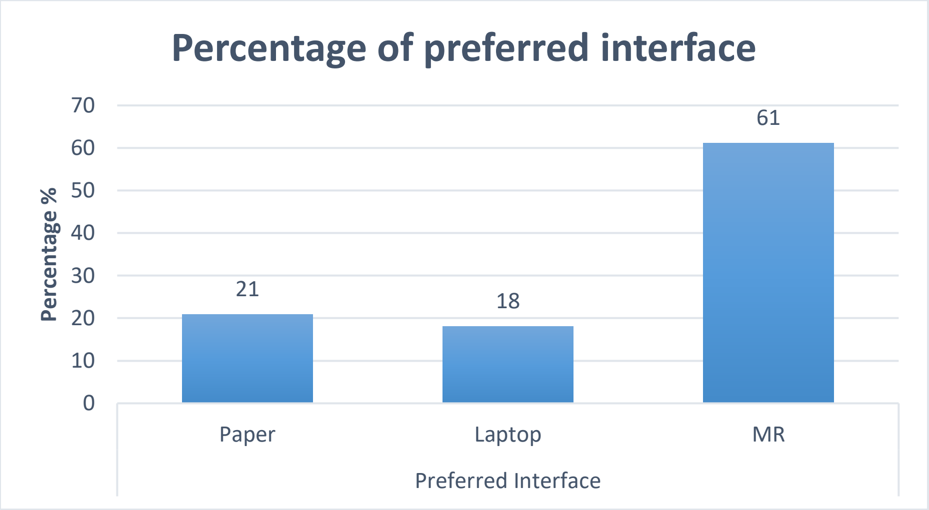


Figure 41 - Percentage of preferred interface to use on a regular basis.

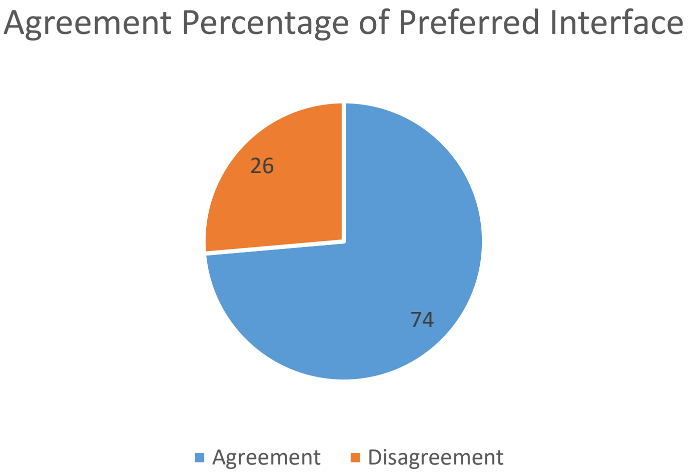


Figure 42 - Agreement Percentage of the preferred interface.

Table 6 - Preference vs Best Performance of interfaces

		Best Performance		
	Interface	**1**	**2**	**3**
Preference	**1**	11	3	4
	2	6	4	6
	3	6	1	38

6.5 Summary

This chapter presented the results obtained from the 3 tests performed by the 72 volunteers that were recruited to complete the experimental procedures to test the ISLVM prototype. The presented data was the information gathered for each participant, the statistical analysis and percentages of the results obtained for the effectiveness variables and the usability questionnaire. The results showed that there was a statistically significant difference in the number of errors committed by each volunteer with the MR interface committing the least amount of errors and the Laptop interface committing the most amount of errors. Furthermore, the MR interface achieved a 94% of successful completions followed by the paper manual with a 71% and the laptop interface with 53% of successful completions. It is also important to mention that all three of the interfaces worked according to their design. That is, for the paper manual, the metrology script that was used functioned without any issues throughout the tests. With regards to the laptop interface both the digital manual on the laptop with the videos, and the metrology script used did not encounter any issues. During experiments that used the MR interface, either the software or the computer crashed on a couple of occasions. Furthermore, there were minor alignment issues with the holograms and very occasional issues relating to recognising voice commands. However, despite these minor issues, the augmentations, holograms, videos and audios all functioned as intended.

7. Discussion

7.1 Introduction

In this chapter, the activities conducted for this research as well as the observations and results of the experimental work are critically discussed. The discussions relate to the aim, objectives and scope of the research and are used to formulate the conclusions and future work in Chapter 8.

7.2 State-Of-The-Art Literature Review of AR in Measurement Applications

The first objective of this research was to review and critically assess the state-of-the-art in measurement assisted assembly with particular reference to key metrology requirements needed at the time of inspection, and the use of AR technologies in manufacturing, verification and validation. This review was documented and critiqued in Chapter 2, and the major challenges and gaps were identified. Based on these gaps, the novelty of this research lies in the MR hardware and metrology instrument combination, and the level of seamless integration that has been achieved between the MR headset, metrology instrument and metrology software . The focus of this study has been on the user performance with ISLVM with clear comparisons with current best practice (laptop and paper interfaces). This research addressed seven out of the nine gaps that were identified in the literature review. Below is a description on how each of these seven gaps has been addressed:

i) Inspection processes suffer from non-optimum procedures for LVM instrument performance.

This gap, together with gap (ii), has been addressed in the specification of the ISLVM. The immersive system provides detailed instructions and explanations on how to correctly use the metrology equipment. Question 9 of the usability questionnaire was included to indicate the retention rate or understanding of the concepts explained in the prototype by the users. The MR interface obtained 82% of correct answers. This question is further discussed and analysed in Section 7.4.2.

ii) There exists a lack of comprehension and implementation of the fundamentals and best practices of LVM, resulting in a poor understanding of the dynamic behaviour of LVM tools and inspection processes.

This gap has been addressed as identified in gap (i) above.

iii) The identification of the challenges that need to be overcome in order to fully incorporate metrology hardware and software with current AR and MR technologies.

Not only were the challenges identified, but a full integration of the MR and metrology technologies was achieved. It was possible for the user to control both the metrology instruments and software through the MR headset which had not been achieved previously. The process on how this was done is described in Chapter 5, Section 5.4 and further discussed in Section 7.4 of this chapter.

iv) The identification of a methodology that allows the presentation of digital information through AR or MR technology in a way that it is easily understood by the user.

This gap was addressed as the first question of the usability questionnaire asked if the interface was easy to understand. The mean response was that the user felt it was easy to understand. This question is further discussed in Section 7.4.2 of this chapter.

v) The majority of AR assembly guidance systems focus on providing a step-by-step instruction, while failing to identify or provide a timely guidance of the instructions in the assembly process.

This gap was addressed as the design of the ISLVM prototype provided the user the ability to not only control the metrology equipment but also control when to move to the next step, or when to receive the next instruction through voice commands. In the developed system, instructions were issued via video, hologram and audio formats.

vi) Most of the case studies found in the literature were performed with simple assemblies. Therefore, future work should focus on the capability of an AR system to provide assistance in a complex, multi-step assembly task.

This gap was set as a requirement for the design of the experiments for the validation and verification of the ISLVM. Although the assembly itself presented little complexity, the measurement task involving the laser tracker and the Spatial Analyzer software was advanced. As such, it could not have been completed if no previous training had been received. This is further detailed in Chapter 5, Section 5.5.

vii) Given that an AR interface could disturb or interrupt an ongoing assembly task, it is important to research the ability to detect and recognize the operator’s actions in order to provide a true industrial hands free system.

This gap was made one of the requirements at the time of selection of the MR technology. The HoloLens provided a hands free immersive system through the use of voice commands. Further details on how this gap was addressed can be found in Chapter 5, Section 5.3 and Section 5.4.

7.3 Specification of an Immersive System for Large Volume Metrology (ISLVM)

The immersive AR system, envisioned in Chapter 4, provides a complete representation of an ISLVM implementation for an in-line assembly process. The philosophy behind the system is to increase the availability of metrology knowledge and measurement data to the operator at the time of assembly inspection. Chapter 4 presented 5 key stages of an inspection process and how the ISLVM prototype could impact each of these stages. However, due to the scope of this research some of the applications of the ISLVM mentioned in Chapter 4 were not implemented in the final prototype. Hence, only the stages that were implemented will be discussed below:

i) Instrument Location: Before taking any assembly measurements, the location and alignment of the metrology instruments in the 3D CAD space. The metrology software is unaware of its workspace and its position relative to the assembly requiring inspection. When a measurement point is taken its X, Y, Z coordinate is given with respect to the instrument's reference system. If it is not done correctly the measurements will not be correct. To do this correctly, several steps are required; the definition and set-up of a reference network, and the procedure on how to locate and align the instrument which both have been explained in detail in Section 4.3. The definition and set-up pf the reference network were not included in this prototype, but the procedure on how to locate and align the instrument was included in the prototype. The ISLVM is able to guide an operator through the procedure on how to locate an instrument in the 3D CAD space, in order to then be able to perform the required inspection. Evidence of this is the fact that to complete the test (regardless if errors in the measurements were made) the participant had to complete the instrument location procedure correctly. Otherwise they were not allowed to continue with the test, and all 72 participants completed the test.

ii) Measurements: Section 4.4 explained the three areas that the ISLVM can assist with at the time of measurement capture. These three areas are measurement guidance, presentation of data, and environmental checks. The current practice for measurement guidance is for the operator to follow a printed or electronic manual. This implies that the operator needs to continually look back and forth between the inspection and the assembly to interpret the manual and locate inspection points correctly.

In addition to this, the majority of inspection processes for large volume metrology is carried out by at least two or more engineers due to the scale of the assemblies, and due to the need to control the metrology software and instruments as the inspection process is taking place. Thus, if an operator needs to perform a set of complex inspection task and has no additional help, the likelihood of committing errors will increase. Through using an implementation of the ISLVM prototype, a single operator is now able to perform an inspection process as both the metrology software and hardware is controlled through the ISLVM. For measurement guidance, the ISLVM prototype removes the likelihood for misinterpretation of instructions, and any ambiguity where to measure as it is able to display directly on to the assembly the exact point that requires measurement. Once the point has been measured it can be displayed on the assembly allowing the operator to keep track of the inspection steps. The advantages gained by reducing the number of operators performing an inspection task and by lowering the likelihood of inspection errors are a reduction in skilled labour cost and time taken to complete the verification process.

iii) Data Analysis and Interpretation of Results: Once data capture from the inspection process has completed, it is important to define how this information is used and presented to the operator performing the verification procedure. As mentioned in the research gaps in Chapter 2, and set as one of the research objectives in Chapter 3, the ISLVM needs to present captured measurement data in a simple intuitive format allowing the operator to make rapid and informed decisions. Currently, there are two companies who have done work in this area, 8tree (8tree, 2017) and Faro with its AR Inspect technology (FARO, 2015). Both technologies have been described in detail in Chapter 2. These technologies do present the information in a simple way that allows the operators to make comparisons, view results and make informed decisions based on the data presented. However, the 8tree technology can only be used on small sections of the assembly at a given time and it can only be used for three very specific verifications. These are the analysis of the flushness of fasteners, dent inspections, and analysis on the size of gaps on an aircraft’s fuselage. Regarding the Faro AR inspect system, there is no current experimental data to provide accurate validations of its use and functionality in a real industrial environment. As mentioned in Chapter 2, MWF’s technology enables large, complex 3D CAD data to be transferred to a tablet device and then used for mobile visualization and comparison to real world conditions. From the information available, FARO AR Inspect appears to be limited to tablets and screens, which either turns the user’s attention away from the assembly or does not allow the user to function hands free. According to Odenthal et al’s. (Odenthal *et al.*, 2014) study on comparing the use of an AR HMD with the use of a Table-Mounted Display (TMD) for assembly error detection the display type does significantly affect the frequency of error detection. Where correct error detection and identification are improved by 36% when using the HMD compared to the TMD. Furthermore FARO AR Inspect does not offer any capabilities to aid with setting up of the instruments, creation of a reference network, nor environment monitoring. It is a system that is tailored for experienced users and relies on the assumption that the user has carried out the previous steps correctly. Section 4.5 describes in detail the capabilities of the ISLVM with respect to data analysis and interpretation of results.

7.4 Testing of the ISLVM through a Participant Based Experimental Study

To evaluate the ISLVM prototype, an industrially inspired experiment was designed and 72 volunteers were asked to complete an inspection task using metrology hardware and software they had never used before. During the experiment, they were asked to follow three different guiding interfaces (Test 1, 2 and 3). Two measures were used to evaluate the three interface systems, namely effectiveness variables and the usability questionnaire. The results obtained from these measures were presented in Chapter 6. The following section analyses and discusses these results.

7.4.1 Discussion on Results Obtained from the Effectiveness Variables

The three variables gathered throughout the experiments were, the time taken to complete the test, number of errors committed during the test, and number of successful completions. The results obtained for each of these variables are presented in Section 6.3. The following is the analysis of these results for each variable:

i) Time taken to complete the test: Completion time was logged to monitor the differences between the tests. Performing the inspection process correctly, without skipping steps and without making mistakes is far more important than saving time. As the volunteers carried out the tests several times with different interfaces, the time taken to complete each test would reduce. The times analysed were only the time for the interface used when it was the participant's first test. As presented in Chapter 6, Section 6.3 the fastest interface was the paper manual, followed by the MR interface, and the slowest average completion time was the laptop interface. It was expected that the paper manual would take the least amount of time as it does not contain videos or audios which the volunteer was forced to listen to. The digital manual on the laptop only had videos and no audio. The MR interface had the same videos plus several explanatory audio recordings, which the user was forced to listen to, with no method to skip forward. Despite this, the digital manual (Test 2) was the slowest interface. This could be attributed to the fact that at the time of taking the measurements when using the laptop the participant had to go back and forth between the assembly and the manual on the screen to identify the next measurement point. Whereas, with the MR interface (Test 3), the points to be measured where overlaid digitally on to the assembly eliminating the need to move or to focus elsewhere. These results are similar to Odenthal et al's. (2014) study, which compared a HMD and a digital manual (accessed through a monitor) and their effect on the detection of assembly errors. Their study found that a HMD increased error detection by 36%; however, a trend towards longer detection rate was found. For the case of this research, this is acceptable, as a priority to higher quality, and fewer performance errors is encouraged. As in LVM, an error typically has greater consequences than completion time. In the case of this research, the MR interface took only 1 minute and 15 seconds longer than the paper manual on average, with fewer performance errors.

ii) Number of errors committed during the test: The results of monitoring this variable will assist in answering the first research question stated in Chapter 3:

"Could the use of modern MR technology enable a single inexperienced participant performing an inspection task to commit less errors than the current tools used in a verification process?"

After conducting appropriate statistical analysis on the data obtained from the experiments (Tests 1-3), Figure 35 shows that none of the confidence intervals of the three different tests overlap. Therefore, there is a significant statistical difference between all three of the tests and thus interfaces used. The interface with the least average errors was the MR interface with a mean of 0.23 errors, followed by the paper manual with a mean of 0.44 errors, and the digital interface with the highest mean with 0.8 errors. In addition to these results, Table 3 and Figure 35 also show that the interface with the least amount of variation is MR, which has the smallest confidence interval also suggesting that it could be the most consistent interface. Therefore, the ISLVM prototype implementation enabled a single inexperienced participant to commit less errors than the current guidance tools whilst performing an assembly inspection task. This can be attributed to the following factors which were observed during the experimental phase:

- One of the biggest sources of error with the paper manual and digital manual during the test was that the metrology hardware would take a measurement whenever it was ready instead of when the participant was ready resulting in erroneous measurements. With the ISLVM prototype, it is possible to control the metrology hardware and software. This enabled the participant to take a measurement whenever they were ready. This created time to make adjustments and check that the right task was being performed, helping to reduce the number of errors.

- The second most common mistake observed during the tests was that the participants would lose the tracking of the laser beam with the SMR because they were turning to the paper manual, or the manual on the laptop's screen to look for the next point to measure. Once the tracking with the SMR is broken, the laser tracker automatically searches for another SMR or source of reflection. Normally, it would find one of the small SMRs from the reference network, which would often lead to a point being captured in the wrong location. The MR technology enabled the displaying of the next point to be taken, directly on top of the assembly. Therefore, it allowed the participant to maintain focus on the task and reduce the likelihood of losing the laser tracking with the SMR, therefore committing less errors. Furthermore, due to the advantages of the first point, even if the volunteer did lose the laser beam from the SMR, the participant would search for which SMR the laser had gone to, "re-capture" the laser beam, and proceed to take the correct measurement.

iii) Number of successful completions: The second research question was:

"Can an operator wearing a MR HMD successfully complete an inspection process?"

The results presented in Table 6 show that the MR interface (Test 3) had the highest success rate with a total of 68 successful completions from 72 trials, resulting in a 94% success rate. It was followed by the paper manual (Test 1) with a 71% success rate and the laptop (Test 2) with the lowest success rate 53%. This again can be attributed to the MR interface being able to reduce the two most common sources of error mentioned previously. Therefore, it is possible for an operator using an ISLVM approach with an MR headset to successfully complete an inspection process with reduced errors.

7.4.2 Discussion on Results Obtained from the Usability Questionnaire

There was a total of 10 questions in the usability questionnaire that were given to each participant throughout the experiments. Analysis and the results obtained from the questionnaires are presented in Section 6.4. Studies have shown that when people work with a positive mind-set their productivity, creativity and engagement increases (Achor, 2012; Oswald, Proto and Sgroi, 2015; Revesencio, 2015) it is important to keep track of how the user is feeling while performing the tests. The most relevant points of the results obtained from each question will be discussed below. When the participants had completed all three tests they were asked what their overall opinion about each interface was, and what aspects they liked and disliked. These responses will also be mentioned and discussed where relevant in the following discussion points:

i) Questions 1 and 2: Questions 1 and 2 asked the user about the ease of use and ease of understanding for each interface. Table 5 shows that both of these questions did not show any statistical significance, and the three medians for both questions were the same with a value of 3 that means they "Totally agree". These results agree with the study of Radkowski et al. (2015) in which they concluded that placing photos instead of assembly information as text and 2D sketches in the paper manual may simplify the task for untrained volunteers such as college students. These results suggest a re-evaluation on how the manuals that are used in the factory floor are written, regardless of which interface is used.

ii) Question 3: This question asked the participants if they felt that they performed quickly with each of the interfaces. Although there was no statistically significant difference in the results, the user's perception scored the same median value of 2 for the paper manual (Test 1) and the digital manual (Test 2) in the laptop despite the paper manual being the quickest of all three test interfaces and the digital manual on the laptop the slowest one. The highest median value of 3 was obtained by the MR interface (Test 3). This suggests that user's perception of time is different than the actual results and could potentially be attributed to how mentally demanding they perceived the interface to be. This was question 6 and the same scenario repeated itself in which both the paper manual and the digital manual in the laptop received the same median score of 2 and the MR interface had a median score of 1.

iii) Question 4: This question asked the users if they were to conduct measurements on a regular basis, which interface would they prefer. The results show that there is a statistically significant difference between the interfaces. This difference was only between the MR interface and both the paper manual and digital manual but not between the paper manual and the digital manual. The results obtained from this question should be comparable to question 10, which asked the participants at the end of the tests to select which interface they would like to work with on a regular basis. That comparison and the participants' opinions on the interfaces will be discussed in relation to question 10.

iv) Question 5: For this question, the participants were asked if they found the interface physically demanding. The results showed that there is a statistically significant difference between the three interfaces. This difference was between the paper manual and the MR interface (Test 3), and the paper manual (Test 1) and the digital manual (Test 2) where the paper manual received the best median score of 1. The digital manual also had a median value of 1; however, the spread of the results and the mean value were higher than for the paper manual. The MR interface received the highest median score of 2. This could be explained by the participant's opinion on the interface in which they said the following:

The majority of the volunteers mentioned that the HoloLens was heavy, uncomfortable, and that most of the weight was felt on the bridge of the nose which by the end of the test was sore.

v) Question 6: Volunteers were asked if they felt that the interface used was mentally demanding. The results show that there is no statistically significant difference between the interfaces. However, the MR interface received the best median score of 1, whereas the other two interfaces had a median score of 2. Most of the opinions from the volunteers on this aspect mentioned that they enjoyed "not having to think", nor interpret any of the instructions, as everything was being "displayed in front" of them and they were being guided step-by-step through the process. One of the participants commented: "It feels like somebody else is in control!"

vi) Question 7: This question asked the volunteers if they found the interface frustrating to use. According to the results there was no statistically significant difference between the interfaces. However, it is important to mention that the MR interface received the worst median score with a value of 2. This is an unexpected result, because if the user felt it was more frustrating than the other two interfaces then they would have chosen to work with any of the other two interfaces, which is not seen in the results of question 4 and question 10. This result could be explained due to a combination of factors, such as the device being uncomfortable to use, some participants struggled with the voice commands (having to repeat commands several times), and on a few occasions the MR system crashed and the volunteers would have to re-start the experiment.

vii) Question 8: Participants were asked if they had fun using this interface. The results show that there was a statistically significant difference between the interfaces. This difference was between the MR interface and the other two interfaces. The difference in the results from the MR interface with respect to the other two interfaces was considerably larger. Only 4 participants out of the 72 choose a value of 2, whereas the rest chose "totally agree" with a value of 3.

To the author's knowledge, this question was not asked in any of the participant based studies found in the literature. This is a subjective question, and the result could be attributed to the novelty of the technology and the first time the volunteers have used it. However, it is of the author's opinion that this result should not be discarded. This is mainly due to research studies stating (Oswald, Proto and Sgroi, 2015; Revesencio, 2015) that when a user is having fun, their productivity increases by 12%, and that despite users feeling the device was uncomfortable, and with some struggling with the voice commands, the majority (68) still said that they enjoyed using the technology.

viii) Question 9: This was not a question related to a usability characteristic but instead to some of the theory explained during the tests. The intention was to see how many correct answers each interface would obtain, and see if the medium by which the information was delivered had an impact on the results. Figure 40 shows that the interface which achieved the highest percentage of correct answers was the digital manual (Test 2) with 92%, followed by the paper manual (Test 1) with 85% and last was the MR interface (Test 3) with 82%. The answer to this question in the paper manual was presented through text, in the digital manual it was explained through a video, and in the MR interface it was the same video used in the digital manual but presented through a hologram of a person explaining the theory. This is important because these results agree with the study of Watson et al. (2008) that concluded that animated assembly instructions facilitate the learning process and help users reduce the learning curve when compared to traditional means of instruction, such as text. This could explain why the digital manual had the highest percentage of correct answers. However, that being said, it would be expected for the MR interface to have achieved a similar percentage, which it did not achieve. A possible explanation could be that as it is new technology with information being presented to the user in a novel, unconventional way, the volunteer may have only been observing and taking in the experience, paying less attention to the explanations. Another factor that could have contributed, is the uncomfortableness of the device which could have distracted the user.

ix) Question 10: This question was only asked at the end of the tests when the volunteers had used all three of the interfaces and it asked them which interface they would like to work with on a regular basis. The preferred interface was the MR interface with 61%, followed by the paper manual with 21%, followed by the digital manual with 18%. These results are also in accordance with question 4 that showed that the volunteers preferred to use the MR interface over the other two interfaces with the difference being statistically significant.

This question was complemented by further analysis to see if the participants had chosen the interface with which they had their best performance (i.e. committed the least amount of errors with). The analysis showed that 74% of the participants did select the interface with that they had the best performance or that was tied with another interface in which they made the same number of errors. Furthermore, Table 6 showed the number of volunteers who were in agreement with their preference and performance (green), and the volunteers who were not in agreement with their preference and performance (red).

What stands out from this table is the big difference in number of volunteers in agreement with their preference and performance for the MR interface (38 volunteers) in comparison to the two other interfaces. Paper was the second highest with a total of 11 volunteers in agreement and the laptop had 4 volunteers in agreement. This result indicates that volunteers did select the MR interface based on the system's ability to improve performance and not on the basis of being a technological novelty.

The results obtained from question 10 and the previous 9 questions can assist in answering the 4th research question stated in Chapter 3:

"Will the comfort of the AR HMD, the physical and mental load generated from the device usage, and how the information is presented to the user through the device have a direct impact on whether the operator prefers to use the ISLVM over current inspection methods?"

The results obtained in this research from the usability questionnaire suggest that the comfort of an interface can affect how well users perform and, therefore, which interface they would like to use on a regular basis. However, after speaking with the participants at the end of all three tests, they commented that the HoloLens was uncomfortable and had some challenging features. Regardless, they still chose the MR interface because of all the capabilities and tools that it offered beyond those of the other interfaces. The comments from the participants that did not choose the MR interface and when asked why they preferred either the paper manual or the digital manual, stated that they were already familiar with this type of interface. These comments seem to suggest the following points:

- Users are willing to sacrifice some degree of comfort in exchange for an equipment that can offer a convenient set of tools that can help them perform better.
- If an ISLVM is introduced as a new tool for inspection, it could be met with resistance by users who tend to resist change. This is an important point, because if the user does not like using the interface they will find reasons not to use it irrespective of its enhanced capabilities.

This questionnaire could be used by other researchers or engineers within industry who are conducting a comparative study between MR and current best practice instruments or procedures within their operation. The fact that this questionnaire was based on previous literature, as specified in Chapter 5, Section 5.8, results are easily comparable with previous studies.

7.5 Limitations of the Experimental Study

There are 3 known limitations associated with the work detailed in this thesis.

i. Volunteers used the HoloLens for the very first time, only once, and for a short period of time. The ISLVM approach needs to be tested in a prolonged study, where the participants need to use the interface for a longer period of time and in an industrial scenario. Hence, the results obtained from the study cannot be treated as final as the prototype has to be put through further testing within an industrial setting.
ii. The ISLVM prototype presented minor hologram misalignments when overlaying the digital content onto the real world objects during measurement capture. An example of this misalignment was that the CAD representation of the granite table and assembly were not 100% aligned. This misalignment was visible; however, it was not major and the inspection process could be conducted. Volunteers were informed of this prior to starting the test, and provided with details on how to mitigate it. This issue could have potentially influenced the total completion time of the test, comfort, frustration, or even performance.
iii. The HoloLens used is a development edition device. Certain aspects such as comfort, field of view, and system crashes, which could have affected the user's perception of the device and their performance during the tests, needs to be treated as temporary obstacles.

7.6 Generalising the Research Findings

Although this work focused on using MR for metrology purposes, this setup could be used in the following scenarios:

i. The methodology that was developed for the specification of the ISLVM can be generalised and applied to other metrology instruments and applications. Figure 23 shows the required components for a generic Immersive System (IS). Furthermore, this methodology can be further generalised and applied to other areas, such as manufacturing or assembly of components. This is reflected in Figure 43, which depicts the Level-0 diagram. Figure 44 (Level-1 diagram) shows an example of this generic methodology being applied to a manufacturing process; however, it can be readily adapted for assembly or metrology.

ii. The third research question in Chapter 3 asked the following:

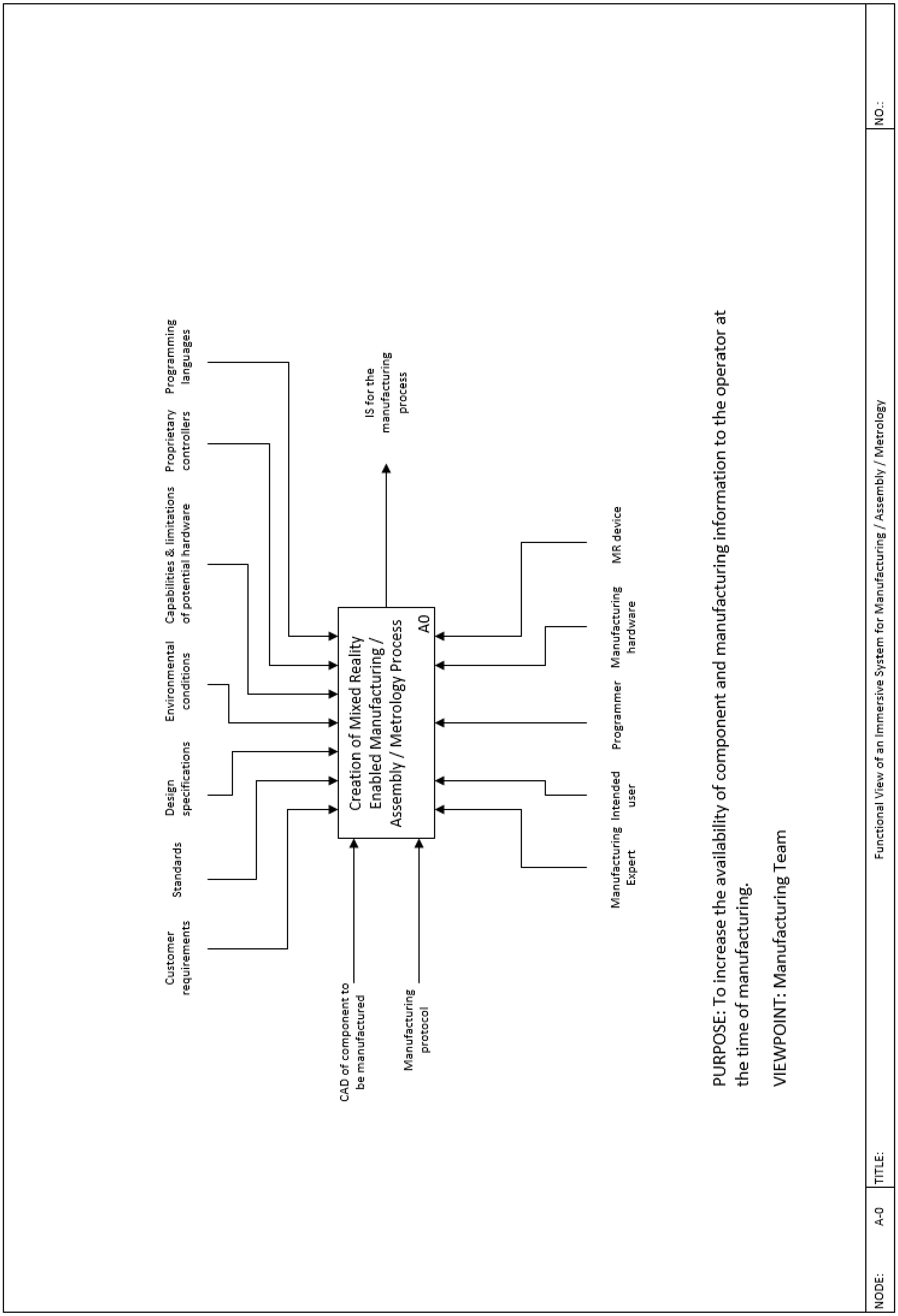
   "Can modern MR technologies integrate seamlessly with current metrology hardware and software in order to be used in an inspection process?"

   The ISLVM prototype in this research proved that the integration of current MR technology with metrology hardware and software is possible. This is a task that had not been achieved before. It is important as it provides evidence that MR technologies can be fully-integrated with metrology resources, which may later be expanded to include other manufacturing and assembly resources. This research has created solutions to many of the initial challenges with this integration, which may be used at a later date by future research efforts. Examples include the differences in programming languages between the interfaces, and the ability to access certain information within proprietary controllers.

iii. The combination of an MR device and measurement or monitoring equipment as part of an interactive support tool can be useful for guiding assemblies or part manufacture in real time. This approach agrees with conclusions from Yamauchi et al. (Yamauchi and Iwamoto, 2010) study in which they used a combined system of AR and an optical measurement instrument to guide an operator in real time through a specific manufacturing task.

iv. The built-in control capabilities of the ISLVM prototype against human mistakes is an advantage that can be used in applications where high quality is required. This idea is in agreement with the conclusions presented in Syberfeldt et al's. (Syberfeldt, Danielsson and Holm, 2015) study.

v. The ISLVM prototype can be used to guide novice users when needing to perform complex tasks in which training and procedural knowledge is limited and any mistakes during the inspection process can be costly. This is in agreement with the conclusions presented in the study by Hou et al. (2013).



PURPOSE: To increase the availability of component and manufacturing information to the operator at the time of manufacturing.

VIEWPOINT: Manufacturing Team

Figure 43 - IDEF0 of IS for Manufacturing

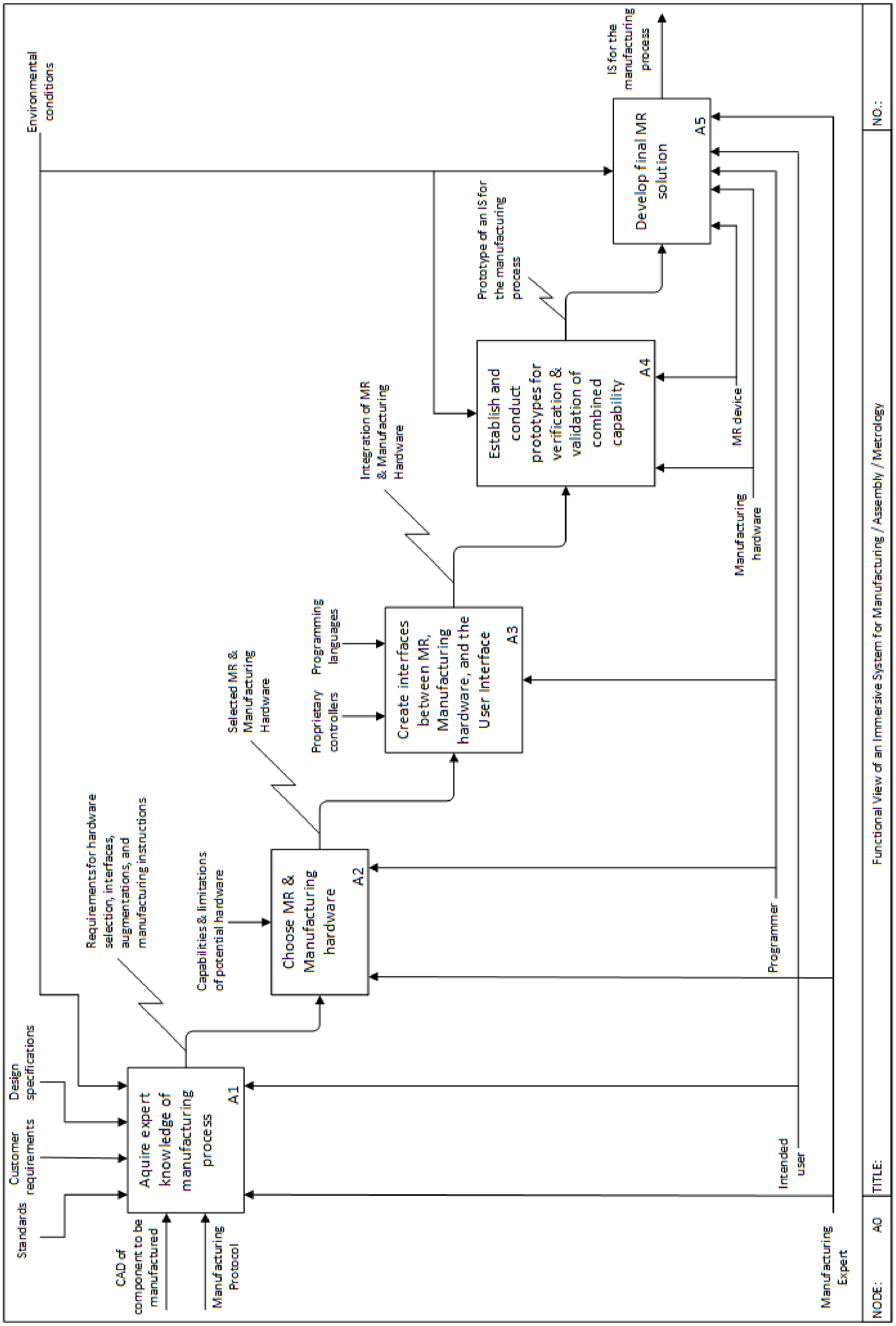


Figure 44 - Detailed IDEF0 of IS for Manufacturing

8. Conclusions and Future Work

8.1 Introduction

The use of large volume metrology (LVM) instruments, such as laser trackers and the expertise required to effectively use them, is regarded as a specialist task within a niche field (metrology and assembly inspection). Training courses for LVM instruments, typically through third party companies, is costly. Due to the complexities of using LVM instruments, user manuals will typically only provide foundational information on how to set up the instrument. They often do not provide information on best practice and measurement considerations. For this reason, it can be challenging for an operator to learn and gain understanding on metrology best practice. Commonly seen within aerospace companies, manuals and procedures are created internally following training as a means for ensuring measurement standardisation. Manuals can be either printed or accessed in digital form through computers or tablets to guide operators through an officially certified process. For this reason, within this research, two guides have been designed for comparison with the ISLVM approach. The first is a printed manual, the second is a digital manual accessed through a laptop. Both manuals contain detailed images and descriptions of the processes to be followed. Based on this, the 4 research questions presented in Chapter 3 will have been answered, followed by further conclusions derived from the work undertaken in this research. In addition to this, suggestions and ideas for future areas of investigation will also be presented.

8.2 Conclusions

1) This research has identified a statistically significant difference in the number of errors committed by volunteers using an MR interface, as opposed to a paper-based or laptop-based instruction guide. The ISLVM MR interface had the least amount of errors committed by each volunteer. This represents an improvement on the interfaces that are currently used within industry (paper and laptop). As such, this supports the hypothesis that the use of an MR system in the inspection process of assemblies will enable a single operator without metrology expertise, to complete a full inspection process while committing fewer errors than paper based and digital methods. However, it is important to mention that the MR interface did present a longer completion time than the paper manual. This point was further discussed in Chapter 7, Section 7.4.1.

2) The results obtained from the experimental procedure show that not only can an operator using the ISLVM approach successfully complete an inspection process, this approach also obtained the highest success rate with 94% of the 72 participants completing a successful inspection procedure.

3) From this research it can be concluded that current MR technologies such as the HoloLens can integrate with metrology hardware and software such as a laser tracker and SpatialAnalyzer. Furthermore, this integrated approach demonstrated promising results and the integration of these new MR technologies with other metrology hardware and software as well as equipment from other industries or processes should be further explored. This point was further discussed in Chapter 7, Section 7.6

4) After analysing the results obtained from the usability questionnaire, it was observed that a decrease in mental work load, user performance with an interface and previous experience with other interfaces are the main drivers in selection of an interface. These factors had a larger effect on user preference for a certain interface than physical comfort, or difficulties with particular features of the interfaces.

5) The ISLVM prototype was able to guide an inexperienced user through the use of a complex metrology instrument, software and inspection procedure. Currently this could have only been achieved by hiring a skilled operator with expertise in metrology to provide the training. This is a promising result for any manufacturing, assembly, or inspection process in which operators are required to perform complex tasks in which training and procedural knowledge is limited, and a mistake in the process can be costly.

6) The built-in control capabilities of the MR system against human mistakes is an advantage that proved to be a key factor on the ISLVM prototype, leading to a reduced number of errors. These capabilities can be used in applications where high quality is required.

7) This research showed that 94% of the participants enjoyed using the MR interface. Thus, using this approach could potentially enhance concentration, engagement, focus, and a better state of mind of an operator, resulting in higher productivity rates and should be considered and further researched.

8) The constraints imposed by the scope of this research and the known limitations of the experimental study mandate that further research is required in this field. As such, this marks the beginning of research that utilises MR technology for metrology purposes. However, the results obtained from this research are promising and can be used to motivate further research that combines MR and metrology hardware and software.

8.3 Contributions to Knowledge

The main contribution to knowledge is that it has been demonstrated that MR technology can be integrated with current metrology hardware and software to create an ISLVM that has the capability of guiding inexperienced users through complex inspection tasks, while committing fewer errors than the current state-of-the-art tools and methods used in industry. Furthermore, as discussed in Chapter 7, Section 7.6 the methodology obtained from the specification and implementation of an ISLVM prototype could be further applied to other areas in metrology and industry such as manufacturing and assembly processes.

8.4 Future Work

While performing this research, a number of opportunities for future work have been identified. These have been separated in short, medium, and long term tasks.

i) Short Term

- Addition of Visual References for Enhanced Alignment

As mentioned in the limitations, during the implementation of the ISLVM, the resulting app presented minor misalignments of the holograms with respect to the real world objects. This was not a major complication for the tests performed and for the task that was carried out by the volunteers. However, if the ISLVM is used in industry this issue would not be acceptable and could have a direct impact on the reliability and quality of the measurements. A correct and reliable inspection relies heavily on the user being able to correctly identify the instructions and the task that is expected for them to perform. The misalignments can cause confusion and uncertainty regarding where to measure or what a certain instruction refers to. This issue could be solved by including an image recognition software that can work with the AR/MR device used and the markers or images employed could potentially work as anchors that could help with aligning the digital content to the real world environment.

- Extension to Longer Tests in an Industrial Scenario

The data obtained from this research was obtained from volunteers that normally do not work in an industrial environment. They have only used the MR device once and for a short period of time. The results obtained are promising. However, further tests should be performed with end users, for a prolonged period and in an industrial setting. This would enable participants to use the interface on repeated occasions to see if the results found in this research remain unchanged under these changing, and demanding circumstances.

ii) Medium Term

- Extension to Other Metrology Hardware and Software

The ISLVM in this research was implemented with the usage of only a laser tracker and SpatialAnalyzer. It is crucial for the development of the ISLVM that its capabilities are extended to the usage of other metrology hardware such as 3D Scanners, Photogrammetry, CMMs, Portable CMMs, and calibration equipment for CMMs. In order for this integration to be possible, the ISLVM needs to be made compatible with the corresponding software for each of these instruments.

- Extending the Usage of the Capabilities of the MR Technology

Due to the definition of the scope of research, there were capabilities of the MR device that were not used during the tests and that could prove to be useful in the industry or other research experiments. Some of these capabilities are the ability of the device to provide visual, and spatial sound guidance to conduct the user through an inspection process when certain holograms are outside the field of view of the HMD. Another capability of the MR device is that it can bring people together collaboratively and solve problems even when they are in different locations. The implementation of the capabilities mentioned above could save time, reduce errors, and enable better interaction and exchange of ideas between people.

- Extending the Scope of the ISLVM

Solving the alignment issue would enable the full implementation of the ISLVM for each of the 5 key stages of an inspection process defined in Chapter 4. The capabilities that could be implemented are the following:

- Assistance with setting-up the metrology hardware.
- Assistance with the actual setting of the reference network. It is imperative to mention that the users will be taught how to locate an instrument and the importance of a reference network. The user will

not just receive assistance with setting up a reference network without understanding the fundamentals and why this is an important step.

- Monitoring of the environmental conditions of the assembly and inspection area.
- Projection of the measurement results on to the actual component.

iii) Long Term

- Implementation of Measurement-Assisted Assembly

This research proved the capability of the ISLVM in providing an interactive support approach for inspecting assemblies. This could open the possibility to start further research into real time measurement-assisted assembly processes in which the ISLVM not only guides an operator through an inspection process, but also exploits its capabilities to guide the operator through the assembly process as well. This has the potential to provide real-time instructions, guidance, notifications if something is going wrong, access to remote assistance to solve an assembly problem, and finally provide results of the assembly on the shop floor of the “go”, “no-go” type. This would allow the operator to make informed decisions with respect to the current state of the assembly. All the while each step, and its successful completion is being recorded, with a customized report sent to the corresponding managers.

References

8tree (2017) *Resource Centre | 8tree*. Available at: http://8-tree.com/resource-centre/ (Accessed: 21 April 2017).

Acer (2017) *Aspire V Nitro | Laptops - High performance encased in style | Acer*. Available at: https://www.acer.com/ac/en/US/content/series/aspirevnitro (Accessed: 31 May 2017).

Achor, S. (2012) *Positive Intelligence*, *Harvard Business Review*. Available at: https://hbr.org/2012/01/positive-intelligence (Accessed: 10 August 2017).

ADAM Technology (2017) *How Does Photogrammetry Work? « ADAM Technology Team Blog*. Available at: http://www.adamtech.com.au/Blog/?p=102 (Accessed: 20 April 2017).

AICON (2015) *AICON 3D Systems - MoveInspect Technology - DPA*. Available at: http://aicon3d.com/products/moveinspect-technology/dpa/technical-details.html (Accessed: 20 April 2017).

Airbus and Bath, U. of (2010) *NGCW SoA Report #8 Large Volume Measurement Technologies (10m+)*.

American Society of Mechanical Engineers. (2009) *Dimensioning and tolerancing : engineering drawings and related documentation practices : an international standard.* American Society of Mechanical Engineers. Available at: https://www.asme.org/products/codes-standards/y145-2009-dimensioning-and-tolerancing (Accessed: 31 August 2017).

Aron, M., Simon, G. and Berger, M.-O. (2007) 'Use of Inertial Sensors to Support Video Tracking', *J. Comput. Augment. Real.*, 18(1), pp. 57–68. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.163.4384&rep=rep1&type=pdf (Accessed: 21 April 2017).

ARToolkit (2017) *Open Source Augmented Reality SDK | ARToolKit.org*. Available at: https://artoolkit.org/ (Accessed: 28 May 2017).

ASME (2006) *B89.4.19 - 2006 Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems*. Available at: https://www.asme.org/products/codes-standards/b89419-2006-performance-evaluation-laserbased (Accessed: 31 August 2017).

Augment (2016) *Infographic: The History of Augmented Reality - Augment News*. Available at: http://www.augment.com/blog/infographic-lengthy-history-augmented-reality/ (Accessed: 19 September 2017).

Bridges, B. (2009) *How Laser Trackers Work | Quality Digest*. Available at: https://www.qualitydigest.com/inside/twitter-ed/how-laser-trackers-work.html# (Accessed: 30 September 2017).

Brough, J. E., Schwartz, M., Gupta, S. K., Anand, D. K., Kavetsky, R. and Pettersen, R. (2007) 'Towards the development of a virtual environment-based training system for mechanical assembly operations', *Virtual Reality*. Springer-Verlag, 11(4), pp. 189–206. doi: 10.1007/s10055-007-0076-4.

Bryman, A. (2016) *Social research methods*. Oxford University Press. Available at: https://books.google.co.uk/books?id=N2zQCgAAQBAJ&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false (Accessed: 25 April 2017).

BuildIT (2017) *BuildIT 3D Metrology Solutions*. Available at: http://www.builditsoftware.com/ (Accessed: 5 September 2017).

Cai, B., Dai, W., Muelaner, J. E. and Maropoulos, P. G. (2009) 'Measurability Characteristics Mapping for Large Volume Metrology Instruments Selection', *ICMR09*, M. doi: 10.2966/scrip.

Charara, S. (2015) *The difference between augmented and virtual reality - raconteur.net*. Available at: https://www.raconteur.net/technology/what-is-the-difference-between-augmented-and-virtual-reality (Accessed: 1 October 2017).

Chryssolouris, G., Mavrikios, D., Fragos, D. and Karabatsou, V. (2000) 'Virtual reality-based experimentation environment for the verification of human-related factors in assembly processes', *Robotics and Computer-Integrated Manufacturing*, 16(4), pp. 267–276. doi: 10.1016/S0736-5845(00)00013-2.

Chryssolouris, G., Mavrikios, D., Fragos, D., Karabatsou, V. and Alexopoulos, K. (2004) 'A Hybrid Approach to the Verification and Analysis of Assembly and Maintenance Processes Using Virtual Reality and Digital Mannequin Technologies', in *Virtual and Augmented Reality Applications in Manufacturing*. London: Springer London, pp. 97–110. doi: 10.1007/978-1-4471-3873-0_6.

Daponte, P., De Vito, L., Picariello, F. and Riccio, M. (2013) 'State of the art and future developments of measurement applications on smartphones', *Measurement*. Elsevier Ltd, 46(9), pp. 3291–3307. doi: 10.1016/j.measurement.2013.05.006.

ElMaraghy, H. and ElMaraghy, W. (2016) 'Smart Adaptable Assembly Systems', *Procedia CIRP*, 44, pp. 4–13. doi: 10.1016/j.procir.2016.04.107.

EPSON (2017) *Moverio BT-200 Smart Glasses (Developer Version Only) | Smart Glasses | Wearables | For Work | Epson US*. Available at: https://epson.com/For-Work/Wearables/Smart-Glasses/Moverio-BT-200-Smart-Glasses-%28Developer-Version-Only%29/p/V11H560020 (Accessed: 27 May 2017).

Erkoyuncu, J. A., del Amo, I. F., Dalle Mura, M., Roy, R. and Dini, G. (2017) 'Improving efficiency of industrial maintenance with context aware adaptive authoring in augmented reality', *CIRP Annals - Manufacturing Technology*, 66(1), pp. 465–468. doi: 10.1016/j.cirp.2017.04.006.

Estler, W. T., Edmundson, K. L., Peggs, G. N. and Parker, D. H. (2002) 'Large-Scale Metrology – An Update', *CIRP Annals*. Elsevier, 51(2), pp. 587–609. doi: 10.1016/S0007-8506(07)61702-8.

EURAMET (2012) 'EMRP Call 2012 – Open Excellence, Industry and SI Broader Scope Title: Large volume metrology in industry Conformity with the Work Programme Background to the Metrological Challenges'. Available at: www.euramet.org (Accessed: 2 October 2017).

EURAMET (2017) *Large Volume Metrology in Industry*. Available at: https://www.euramet.org/research-innovation/search-research-projects/details/?eurametCtcp_project_show[project]=1159 (Accessed: 2 October 2017).

FARO (2009) *Laser Trackers – IFM vs ADM Technology*. Available at: http://farotechnologies.blogspot.co.uk/2009/09/laser-trackers-ifm-vs-adm-technology.html (Accessed: 30 September 2017).

FARO (2015) 'Augmented Reality Metaio Engineer', *Brochure*.

FARO (2017) *FARO Laser Tracker - Laser Tracking Solutions*. Available at: http://www.faro.com/products/metrology/faro-laser-tracker/overview (Accessed: 20 April 2017).

Flack, D. and Hannaford, J. (2005) 'Measurement Good Practice Guide No. 80: Fundamental Good Practice in Dimensional Metrology', (80).

Foundry (2016) *VR/AR/MR, what's the difference? | Virtual reality | Foundry*. Available at: https://www.foundry.com/industries/virtual-reality/vr-mr-ar-confused (Accessed: 4 September 2017).

Francis, A., Maropoulos, P., Mullineux, G. and Keogh, P. (2016) 'Design for Verification', *Procedia CIRP*, 56, pp. 61–66. doi: 10.1016/j.procir.2016.10.017.

Friedrich, W. and Friedrich, W. (2002) 'ARVIKA: Augmented Reality for Development, Production and Service', *The 1st International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 3–4. doi: 10.1109/ISMAR.2002.1115059.

Gattullo, M., Uva, A. E., Fiorentino, M. and Gabbard, J. L. (2015) 'Legibility in Industrial AR: Text Style, Color Coding, and Illuminance', *IEEE Computer Graphics and Applications*, 35(2), pp. 52–61. doi: 10.1109/MCG.2015.36.

Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U. and Tecchia, F. (2013) 'Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks', *Interactive Learning Environments*. Taylor & Francis, 4820(November 2014), pp. 1–21. doi: 10.1080/10494820.2013.815221.

Geomagic (2016) *3D scanning, design and reverse engineering software from 3D Systems Geomagic*. Available at: http://www.geomagic.com/en/ (Accessed: 5 September 2017).

Google (2017) *Google Cardboard - Official VR Headset - Google Store*. Available at: https://store.google.com/product/google_cardboard?utm_source=en_GB-ha-emea-sem&utm_medium=text&utm_term=GoogleCardboard-exact&utm_content=bkws&utm_campaign=googlecardboard&gclid=CjwKCAjw_8jNBRB-EiwA96Yp1gTOTAmxQJeqm8jdgQuBb2n9lL4fCPafHlQWJQ6rZTPRYVbPaQjGo (Accessed: 8 September 2017).

Henderson, S. and Feiner, S. (2011) 'Exploring the benefits of augmented reality documentation for maintenance and repair', *IEEE Transactions on Visualization and Computer Graphics*, 17(10), pp. 1355–1368. doi: 10.1109/TVCG.2010.245.

Hexagon (2017) *Leica Reflectors for Fixed Installation (RFI) 0.5", Set of 5 pcs. - Tracker Acc.* Available at: https://store.hexagonmetrology.us/laser-tracker-accessories/leica-reflectors-for-fixed-installation-rfi-0-5 (Accessed: 6 June 2017).

Hexagon Metrology (2011a) 'CMS – 3D point scanning at its best'.

Hexagon Metrology (2011b) 'Romer Absolute Arm'. Available at: http://w3.leica-geosystems.com/downloads123/hxrom/romer/general/brochures/ROMER Absolute Arm Product Brochure_en.pdf (Accessed: 12 September 2017).

Hou, L. and Wang, X. (2013) 'A study on the benefits of augmented reality in retaining working memory in assembly tasks: A focus on differences in gender', *Automation in Construction*, 32, pp. 38–45. doi: 10.1016/j.autcon.2012.12.007.

Hou, L., Wang, X., Bernold, L. and Love, P. (2013) ‘Using Animated Augmented Reality to Cognitively Guide Assembly’, *Journal of Computing in Civil Engineering*, (October), pp. 439–451. doi: 10.1061/(ASCE)CP.1943-5487.0000184.

Hughes, B., Forbes, A., Lewis, A., Sun, W., Veal, D. and Nasr, K. (2011) ‘Laser tracker error determination using a network measurement’, *Meas. Sci. Technol. Meas. Sci. Technol*, 22(22), p. 12. doi: 10.1088/0957-0233/22/4/045103.

Innovmetric (2017) *InnovMetric Software | Your 3D Metrology Software Partner*. Available at: https://www.innovmetric.com/ (Accessed: 5 September 2017).

ISO 14253-2:2011 (2011) *Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measring equipment - Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product Verification*. Available at: https://bsol-bsigroup-com.ezproxy1.bath.ac.uk/PdfViewer/Viewer?pid=000000000030288279 (Accessed: 22 May 2017).

JCGM, J. C. F. G. I. M. (2008) ‘Evaluation of measurement data — Guide to the expression of uncertainty in measurement’, *International Organization for Standardization Geneva ISBN*, 50(September), p. 134. doi: 10.1373/clinchem.2003.030528.

Johnson, E. (2016) *What are the differences among virtual, augmented and mixed reality? - Recode*. Available at: https://www.recode.net/2015/7/27/11615046/whats-the-difference-between-virtual-augmented-and-mixed-reality (Accessed: 1 October 2017).

Kay, M. (2017) *30 Top VR & AR Terms You Need to Know for 2017*. Available at: https://www.gearbrain.com/top-vr-ar-terms-glossary-1855014455.html (Accessed: 1 October 2017).

Khuong, B. M., Kiyokawa, K., Miller, A., La Viola, J. J., Mashita, T. and Takemura, H. (2014) ‘The effectiveness of an AR-based context-aware assembly support system in object assembly’, *Proceedings - IEEE Virtual Reality*, pp. 57–62. doi: 10.1109/VR.2014.6802051.

Kinematics, N. R. (2013) *SpatialAnalyzer User Manual*. doi: 10.1007/SpringerReference_28001.

Kinematics, N. R. (2017) *Spatial Analyzer*. Available at: http://www.kinematics.com/.

Klaas, E., Chhabra, A. and Bottcher, P. (2013) ‘Usability engineering: The surface becomes the (touch) screen’. Available at: http://8-tree.com/wp-content/uploads/2014/06/CMSC-2013-Usability-engineering-final.pdf (Accessed: 21 April 2017).

Krevelen, D. W. F. van and Poelman, R. (2010) ‘A Survey of Augmented Reality Technologies, Applications and Limittions’, *The International Journal of Virtual Reality*, 9(2), pp. 1–20. doi: 10.1155/2011/721827.

Laerd Statistics (2013) *Friedman Test in SPSS Statistics - How to run the procedure, understand the output using a relevant example | Laerd Statistics.* Available at: https://statistics.laerd.com/spss-tutorials/friedman-test-using-spss-statistics.php (Accessed: 10 July 2017).

Lang, P., Kusej, A., Pinz, A. and Brasseur, G. (2002) ‘Inertial tracking for mobile augmented reality’, *IMTC/2002. Proceedings of the 19th IEEE Instrumentation and Measurement Technology Conference (IEEE Cat. No.00CH37276)*, 2(May), pp. 1583–1587. doi: 10.1109/IMTC.2002.1007196.

Lee, H. and Yoon, G. (2004) 'A Computer-Aided Inspection Planning System for On-Machine Measurement -Part I : Global Inspection Planning-', *KSME International Journal*, 18(8), pp. 1349–1357.

LEGO (2017) *DUPLO LEGO.com*. Available at: https://www.lego.com/en-gb/duplo/toddlertruth (Accessed: 8 June 2017).

Leica (2012) 'leica absolute tracker at401'. Available at: http://w3.leica-geosystems.com/downloads123/m1/metrology/AT401/brochures/Leica Absolute Tracker AT401_en.pdf (Accessed: 7 September 2017).

Lewis, A. J., Campbell, M. and Stavroulakis, P. (2016) 'Performance evaluation of a cheap, open source, digital environmental monitor based on the Raspberry Pi', *Measurement*. Elsevier, 87, pp. 228–235. doi: 10.1016/J.MEASUREMENT.2016.03.023.

LUMINAR and EURAMET (2016) 'Final Publishable JRP Summary for IND53 LUMINAR Large Volume Metrology in Industry IND53 LUMINAR', M(August), pp. 1–5.

Makris, S., Karagiannis, P., Koukas, S. and Matthaiakis, A. S. (2016) 'Augmented reality system for operator support in human-robot collaborative assembly', *CIRP Annals - Manufacturing Technology*. CIRP, 65(1), pp. 61–64. doi: 10.1016/j.cirp.2016.04.038.

Maropoulos, P. G. and Ceglarek, D. (2010) 'Design verification and validation in product lifecycle', *CIRP Annals - Manufacturing Technology*, 59(2), pp. 740–759. doi: 10.1016/j.cirp.2010.05.005.

Maropoulos, P. G., Guo, Y., Jamshidi, J. and Cai, B. (2008) 'Large volume metrology process models: A framework for integrating measurement with assembly planning', *CIRP Annals - Manufacturing Technology*, 57(1), pp. 477–480. doi: 10.1016/j.cirp.2008.03.017.

Meiners-Hagen, K., Meyer, T., Prellinger, G., Pöschel, W., Dontsov, D. and Pollinger, F. (2016) 'Overcoming the refractivity limit in manufacturing environment', *Optics Express*. Optical Society of America, 24(21), p. 24092. doi: 10.1364/OE.24.024092.

Merriam-Webster (2017) *Happiness | Definition of Happiness by Merriam-Webster*. Available at: https://www.merriam-webster.com/dictionary/happiness (Accessed: 7 November 2017).

Metrolog (2017) *Metrolog XG*. Available at: http://www.metrologic.fr/en-us/products/software/metrologxg.aspx (Accessed: 5 September 2017).

Microsoft (2017a) *Microsoft Mixed Reality Academy*. Available at: https://developer.microsoft.com/en-us/windows/mixed-reality/academy (Accessed: 7 November 2017).

Microsoft (2017b) *Visual Studio IDE, Code Editor, Team Services, & Mobile Center*. Available at: https://www.visualstudio.com/ (Accessed: 14 June 2017).

Microsoft Commercial (2017) *Business Innovation with Holographic Technology | HoloLens*. Available at: https://www.microsoft.com/en-gb/hololens/commercial-overview (Accessed: 19 September 2017).

Microsoft Hololens (2017) *No Title*. Available at: https://www.microsoft.com/microsoft-hololens/en-us.

Miller, R. (2015) *Apple Acquires Augmented Reality Company Metaio | TechCrunch*. Available at: https://techcrunch.com/2015/05/28/apple-metaio/ (Accessed: 19 September 2017).

Muelaner, J. (2015) *Length Measurement - Dr Jody Muelaner*. Available at: http://www.muelaner.com/length-measurement/ (Accessed: 20 April 2017).

Muelaner, J. E., Cai, B. and Maropoulos, P. G. (2009) 'LARGE VOLUME METROLOGY INSTRUMENT SELECTION AND MEASURABILITY ANALYSIS', *Proceedings of DET2009*, 66, pp. 1027–1041.

Muelaner, J. E. and Maropoulos, P. G. (2014) 'Large Volume Metrology Technologies for the Light Controlled Factory', *Procedia CIRP*. Elsevier, 25, pp. 169–176. doi: 10.1016/J.PROCIR.2014.10.026.

MWF Technology (2017) *jipAR*. Available at: http://www.mwf-technology.de/en/software/jipAR.html (Accessed: 8 August 2017).

Nikon (2017) *Laser Radar MV331/351 | Laser Radar | Large volume metrology | Nikon Metrology*. Available at: https://www.nikonmetrology.com/en-us/product/laser-radar-mv331-351 (Accessed: 19 September 2017).

Nikon Corporation (2017) 'Nikon Laser Radar MV331 / MV351'. Available at: https://www.nikonmetrology.com/images/brochures/laser-radar-general-en.pdf (Accessed: 19 September 2017).

Nikon Metrology (2017) 'Nantes' leadership in composite part manufacturing'. Available at: https://www.nikonmetrology.com/images/case-studies/airbus-laser-radar-en.pdf (Accessed: 19 September 2017).

NPL (2017) *Large Volume Dimensional Metrology : Dimensional : Science + Technology : National Physical Laboratory*. Available at: http://www.npl.co.uk/science-technology/dimensional/large-volume-dimensional-metrology (Accessed: 15 August 2017).

Oculus (2017) *Oculus Rift | Oculus*. Available at: https://www.oculus.com/rift/ (Accessed: 8 September 2017).

Odenthal, B., Ph., M. M., Wolfgang, K. and M., S. C. (2014) 'A Comparative Study of Head-Mounted and Table-Mounted Augmented Vision Systems for Assembly Error Detection', *Human Factors and Ergonomics in Manufacturing*, 24, pp. 105–123.

Ong, S. K., Pang, Y. and Nee, A. Y. C. (2007) 'Augmented Reality Aided Assembly Design and Planning', *CIRP Annals - Manufacturing Technology*, 56(1), pp. 49–52. doi: 10.1016/j.cirp.2007.05.014.

Optinvent (2017) *Optinvent*. Available at: http://www.optinvent.com/ (Accessed: 27 May 2017).

Oswald, A. J., Proto, E. and Sgroi, D. (2015) 'Happiness and Productivity', *Journal of Labor Economics*, 33(4). Available at: http://www.journals.uchicago.edu/doi/pdfplus/10.1086/681096 (Accessed: 10 August 2017).

Oxford Dictionaries (2017) *unhappiness | Definition of unhappiness in English by Oxford Dictionaries*. Available at: https://en.oxforddictionaries.com/definition/unhappiness (Accessed: 7 November 2017).

Palmarini, R., Erkoyuncu, J. A. and Roy, R. (2017) 'An Innovative Process to Select Augmented Reality (AR) Technology for Maintenance', *Procedia CIRP*, 59, pp. 23–28. doi: 10.1016/j.procir.2016.10.001.

Pappas, M., Mavrikios, D., Karabatsou, V. and Chryssolouris, G. (2006) 'VR-Based Methods and Developments for Assembly Verification', *1st CIRP International Seminar on Assembly Systems (ISAS 2006)*, pp. 295–300.

Radkowski, R., Herrema, J. and Oliver, J. (2015) 'Augmented Reality-Based Manual Assembly Support With Visual Features for Different Degrees of Difficulty', *International Journal of Human-Computer Interaction*, 31(5), pp. 337–349. doi: 10.1080/10447318.2014.994194.

Re, G. M. and Bordegoni, M. (2014) ‘An Augmented Reality Framework for Supporting and Monitoring Operators during Maintenance Tasks’, *VAMR 2014, Part II*, 8526, pp. 443–454.

Rentzos, L., Papanastasiou, S., Papakostas, N. and Chryssolouris, G. (2013) *Augmented reality for human-based assembly: Using product and process semantics*, *12th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design, and Evaluation of Human - Machine Systems, HMS 2013*. IFAC. doi: 10.3182/20130811-5-US-2037.00053.

Revesencio, J. (2015) *Why Happy Employees Are 12% More Productive*, *Fast Company*. Available at: https://www.fastcompany.com/3048751/happy-employees-are-12-more-productive-at-work (Accessed: 10 August 2017).

Robson, S., Macdonald, L., Kyle, S. and Shortis, M. R. (2016) ‘CLOSE RANGE CALIBRATION OF LONG FOCAL LENGTH LENSES IN A CHANGING ENVIRONMENT’, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B5. doi: 10.5194/isprsarchives-XLI-B5-115-2016.

Rolland, J. P., Baillot, Y. and Goon, A. A. (2001) ‘A SURVEY OF TRACKING TECHNOLOGY FOR VIRTUAL ENVIRONMENTS’, pp. 67–112. Available at: https://pdfs.semanticscholar.org/ce53/48128f94f3383bdc4eb15fb4eaf3721d521f.pdf (Accessed: 21 April 2017).

Rooks, B. (1998) ‘A shorter product development time with digital mock-up’, *Assembly Automation*, 18(1), pp. 34–38. doi: 10.1108/01445159810201405.

Shuttleworth, M. (2017) *Counterbalanced Measures Design - Counterbalancing Test Groups*. Available at: https://explorable.com/counterbalanced-measures-design (Accessed: 13 June 2017).

Singh, P. K., Jain, P. K. and Jain, S. C. (2009) ‘Important issues in tolerance design of mechanical assemblies. Part 2: Tolerance synthesis’, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 223(10), pp. 1249–1287. doi: 10.1243/09544054jem1304b.

Sony (2017) *SmartEyeglass Developer Edition SED-E1 – Developer World*. Available at: https://developer.sonymobile.com/products/smarteyeglass/ (Accessed: 27 May 2017).

Stork, S. and Schubö, A. (2010) ‘Human cognition in manual assembly: Theories and applications’, *Advanced Engineering Informatics*. Elsevier Ltd, 24(3), pp. 320–328. doi: 10.1016/j.aei.2010.05.010.

Syberfeldt, A., Danielsson, O. and Holm, M. (2015) ‘Visual Assembling Guidance Using Augmented Reality’, *Procedia Manufacturing*. Elsevier B.V., 1, pp. 98–109. doi: 10.1016/j.promfg.2015.09.068.

Tang, A., Owen, C., Biocca, F. and Mou, W. (2003) ‘Comparative effectiveness of augmented reality in object assembly’, *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, (5), pp. 73–80. doi: 10.1145/642625.642626.

Tiefenbacher, P., Lehment, N. H. and Rigoll, G. (2014) ‘Augmented Reality Evaluation : A Concept Utilizing Virtual Reality’, *Virtual Augmented and Mixed Reality. Designing and Developing Virtual and Augmented Environments*, 8525, pp. 226–236.

Unity (2017) *Unity - Game Engine*. Available at: https://unity3d.com/ (Accessed: 12 September 2017).

University of Bath and LUMINAR EMRP Project (2016) ‘Coping with Thermal Expansion in Large Volume Metrology Good Practice Guide’. Available at: http://projects.npl.co.uk/luminar/publications/luminar-gpg-thermal-expansion-lvm.pdf (Accessed: 2 October 2017).

Verisurf (2017) *Verisurf Software, Inc. - The Leader in Model-based Inspection and Reverse Engineering.* Available at: https://www.verisurf.com/ (Accessed: 5 September 2017).

Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D. and Marin, F. (2013) ‘Innovative system for real-time ergonomic feedback in industrial manufacturing’, *Applied Ergonomics*. Elsevier Ltd, 44(4), pp. 566–574. doi: 10.1016/j.apergo.2012.11.008.

Vive (2017) *VIVE^{TM} United Kingdom | Buy Vive Hardware*. Available at: https://www.vive.com/uk/product/ (Accessed: 8 September 2017).

Vuforia (2017) *Vuforia | Augmented Reality*. Available at: https://www.vuforia.com/ (Accessed: 28 May 2017).

Vuzix (2017) *Vuzix | View The Future*. Available at: https://www.vuzix.com/Products/m100-smart-glasses (Accessed: 27 May 2017).

Walford, A. (2007) *What is Photogrammetry?* Available at: http://www.photogrammetry.com/ (Accessed: 20 April 2017).

Wang, G. (2002) ‘Definition and Review of Virtual Prototyping’, *Journal of Computing and Information Science in Engineering*, 2(3), pp. 232–237. doi: 10.1115/1.1526508.

Wang, X., Ong, S. K. and Nee, A. Y. C. (2016) ‘A comprehensive survey of augmented reality assembly research’, *Advances in Manufacturing*. Shanghai University, 4(1), pp. 1–22. doi: 10.1007/s40436-015-0131-4.

Watson, G., Curran, R., Butterfield, J., Craig, C. and Student, P. (2008) ‘The Effect of Using Animated Work Instructions Over Text and Static Graphics When Performing a Small Scale Engineering Assembly’, *Collaborative Product and Service Life Cycle Management for a Sustainable World*, pp. 541–550. Available at: https://link.springer.com/content/pdf/10.1007/978-1-84800-972-1_51.pdf (Accessed: 12 August 2017).

Wiedenmaier, S., Oehme, O., Schmidt, L. and Luczak, H. (2003) ‘Augmented reality (AR) for assembly processes design and experimental evaluation’, *International journal of Human-Computer Interaction*, 16(3), pp. 497–514. doi: 10.1207/S15327590IJHC1603.

Wikitude (2017) *Wikitude - Get Started With The World’s Leading Augmented Reality SDK*. Available at: https://www.wikitude.com/ (Accessed: 28 May 2017).

Witte (2017) *Witte Fixtures & Jigs*. Available at: https://www.witteamerica.com/products/modular-fixturing-systems/fixtures-jigs.php (Accessed: 6 June 2017).

Worn, H., Frey, D. and Keitel, J. (2000) ‘Digital factory - planning and running enterprises of the future’, *2000 26th Annual Conference of the IEEE Industrial Electronics Society. IECON 2000. 2000 IEEE International Conference on Industrial Electronics, Control and Instrumentation. 21st Century Technologies and Industrial Opportunities (Cat. No.00CH37141)*, 2, pp. 1286–1291. doi: 10.1109/IECON.2000.972307.

Wright, I. (2016) *Laser Trackers – From Inspection to Manufacturing > ENGINEERING.com*. Available at: http://www.engineering.com/AdvancedManufacturing/ArticleID/13499/Laser-Trackers-From-Inspection-to-Manufacturing.aspx (Accessed: 12 September 2017).

Yamauchi, M. and Iwamoto, K. (2010) 'Combination of optical shape measurement and augmented reality for task support: II. Real-time feedback of shape measurement results', *Optical Review*, 17(3), pp. 269–274. doi: 10.1007/s10043-010-0047-y.

Yang, B., Ross-Pinnock, D., Muelaner, J. and Mullineux, G. (2017) 'Thermal compensation for large volume metrology and structures', *International Journal of Metrology and Quality Engineering*, 8(21). doi: 10.1051/ijmqe/2017004.

Yin, X., Gu, Y., Qiu, S. and Fan, X. (2015) 'VR&AR Combined Manual Operation Instruction System on Industry Products: A Case Study', *Proceedings - 2014 International Conference on Virtual Reality and Visualization, ICVRV 2014*, (August 2014), pp. 65–72. doi: 10.1109/ICVRV.2014.55.

Zhao, F., Xu, X. and Xie, S. Q. (2009) 'Computer-Aided Inspection Planning-The state of the art', *Computers in Industry*, 60(7), pp. 453–466. doi: 10.1016/j.compind.2009.02.002.

Zhu, Z., Branzoi, V., Vitovitch, N. and Yarnall, L. (2014) 'AR-Mentor : Augmented Reality Based Mentoring System', *IEEE International Symposium on Mixed and Augmented Reality 2014 Science and Technology Proceedings*, pp. 17–22.

Appendix A – SpatialAnalyzer Metrology Script

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;
using System.Runtime.InteropServices;

using SpatialAnalyzerSDK;

namespace SDKTesterCSharp
{
    public partial class Form1 : Form
    {
        ISpatialAnalyzerSDK NrkSdk = new SpatialAnalyzerSDKClass();

        enum MPStatus
        {
            SdkError = -1,
            Undone = 0,
            InProgress = 1,
            DoneSuccess = 2,
            DoneFatalError = 3,
            DoneMinorError = 4,
            CurrentTask = 5
        };

        #region variables
        int instId;
        double value;
        double value1;
        double value2;
        double value3;
        #endregion


        public Form1()
        {
            InitializeComponent();
        }

        private void button1_Click(object sender, EventArgs e)
        {
            String host = "localhost";
            if (!NrkSdk.Connect(host))
               {
                      MessageBox.Show("Unable to Connect!");
               }
        }

        private void button2_Click(object sender, EventArgs e)
        {
```

```
            NrkSdk.SetStep("New SA File");
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Open SA File");
            NrkSdk.SetFilePathArg("SA File Name", "D:\\Documents\\PhD\\AR
Project\\Experiment\\PhD_Experiment.xit64", false);
            NrkSdk.ExecuteStep();

            /*
            NrkSdk.SetStep("Ask for String");
            NrkSdk.SetStringArg("Question to ask", "Please write the Name of the new
Collection:");
            NrkSdk.SetBoolArg("Password Entry?", false);
            NrkSdk.SetStringArg("Initial Answer", "");
            NrkSdk.SetFontTypeArg("Font", "MS Shell Dlg", 18, 0, 0, 0);
            NrkSdk.ExecuteStep();

            string sValue = null;
            NrkSdk.GetStringArg("Answer", sValue);
            string name = sValue;
            */
            NrkSdk.SetStep("Construct Collection");
            NrkSdk.SetCollectionNameArg("Collection Name", "Position_3");
            NrkSdk.SetStringArg("Folder Path", "");
            NrkSdk.SetBoolArg("Make Default Collection?", true);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Add New Instrument");
            // "Leica TS30 Total Station", "Ubisense RTLS",
            NrkSdk.SetInstTypeNameArg("Instrument Type", "Leica emScon AT401");
            NrkSdk.ExecuteStep();

            string sCol = null;
            NrkSdk.GetColInstIdArg("Instrument Added (result)", sCol, instId);
            string colName = sCol;

            NrkSdk.SetStep("Start Instrument Interface");
            NrkSdk.SetColInstIdArg("Instrument's ID", "Position_3", 0);
            NrkSdk.SetBoolArg("Initialize at Startup", true);
            NrkSdk.SetStringArg("Device IP Address (optional)", "");
            NrkSdk.SetIntegerArg("Interface Type (0=default)", 0);
            NrkSdk.SetBoolArg("Run in Simulation", false);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Locate Instrument (Ref. Tie-In)");
            NrkSdk.SetColInstIdArg("Instrument to Locate", "Position_3", 0);
            NrkSdk.SetCollectionObjectNameArg("Reference Group Name", "A",
"Ref_Network");
            NrkSdk.SetCollectionObjectNameArg("Actuals Group Name (to be measured)", "",
"Locate_Inst3");
            NrkSdk.SetDoubleArg("Tolerance", 0.000000);
            NrkSdk.SetBoolArg("Auto Survey", false);
            NrkSdk.ExecuteStep();


            NrkSdk.SetStep("Dock Instrument Interface");
            NrkSdk.SetColInstIdArg("Instrument ID", "Position_3", 0);
            NrkSdk.SetBoolArg("Dock Interface?", true);
```

```
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Configure and Measure");
            NrkSdk.SetColInstIdArg("Instrument's ID", "Position_3", 0);
            NrkSdk.SetPointNameArg("Target Name", "Position_3", "Measurement_3", "p1");
            NrkSdk.SetStringArg("Measurement Mode", "Fast Stable Pts. To SA");
            NrkSdk.SetBoolArg("Measure Immediately", true);
            NrkSdk.SetBoolArg("Wait for Completion", true);
            NrkSdk.SetDoubleArg("Timeout in Seconds", 0.000000);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Make Groups to Objects Relationship");
            NrkSdk.SetCollectionObjectNameArg("Relationship Name", "", "Relationship3");
            object[] objectNameList1 = new object[1];
            objectNameList1[0] = "Position_3::Measurement_3::Point Group";
            object var = new VariantWrapper(objectNameList1);
            NrkSdk.SetCollectionObjectNameRefListArg("Point Groups in Relationship", ref
var);
            object[] objNameList = new object[4];
            objNameList[0] = "CAD::Assembly_PhD: Long_bar: _23560::Surface";
            objNameList[1] = "CAD::Assembly_PhD: Medium_bar: _23559::Surface";
            objNameList[2] = "CAD::Assembly_PhD: Medium_bar::Surface";
            objNameList[3] = "CAD::Assembly_PhD: Long_bar::Surface";
            object var1 = new VariantWrapper(objNameList);
            NrkSdk.SetCollectionObjectNameRefListArg("Objects in Relationship", ref
var1);
            NrkSdk.SetProjectionOptionsArg("Projection Options", "Object To Probe
Vectors", false, false, 0.000000, false, 0.000000);
            NrkSdk.SetBoolArg("Auto Update a Vector Group?", false);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Move Collections by Minimizing Relationships");
            object[] stringList = new object[1];
            stringList[0] = "Position_3";
            object var2 = new VariantWrapper(stringList);
            NrkSdk.SetStringRefListArg("Collections To Move", ref var2);
            NrkSdk.SetBoolArg("Perform 'Direct' Search", false);
            NrkSdk.SetFitDofOptionsArg("Motion to allow", true, true, true, true, true,
true, true);
            NrkSdk.SetBoolArg("Use Fit Dialog", false);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Query Groups to Objects");
            object[] objNameList2 = new object[1];
            objNameList2[0] = "Position_3::Measurement_3::Point Group";
            object var3 = new VariantWrapper(objNameList2);
            NrkSdk.SetCollectionObjectNameRefListArg("Group Name List (Groups to
Project)", ref var3);
            object[] objNameList3 = new object[4];
            objNameList3[0] = "CAD::Assembly_PhD: Long_bar: _23560::Surface";
            objNameList3[1] = "CAD::Assembly_PhD: Medium_bar: _23559::Surface";
            objNameList3[2] = "CAD::Assembly_PhD: Medium_bar::Surface";
            objNameList3[3] = "CAD::Assembly_PhD: Long_bar::Surface";
            object var4 = new VariantWrapper(objNameList3);
            NrkSdk.SetCollectionObjectNameRefListArg("Object Name List (Objects to
Project to)", ref var4);
            NrkSdk.SetCollectionObjectNameArg("Resulting Object Name", "Position_3",
"Vector_Group_3");
```

```
            NrkSdk.SetProjectionOptionsArg("Projection Options", "Object To Probe
Vectors", false, false, 0.000000, false, 0.000000);
            NrkSdk.SetDoubleArg("RMS Tolerance (0.0 for none)", 0.000000);
            NrkSdk.SetDoubleArg("Maximum Absolute Tolerance (0.0 for none)", 0.000000);
            NrkSdk.SetBoolArg("Show Results Dialog?", true);
            NrkSdk.ExecuteStep();

            NrkSdk.GetDoubleArg("RMS Deviation", value);
            NrkSdk.GetDoubleArg("Max Absolute Deviation", value1);
            NrkSdk.GetDoubleArg("Average Deviation", value2);
            NrkSdk.GetDoubleArg("Standard Deviation", value3);

            /*
            NrkSdk.SetStep("Set point of view");
            NrkSdk.SetViewNameArg("View Name", "PhD_Exp");
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Capture Current View");
            NrkSdk.SetViewNameArg("Picture Name", "Picture3");
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Generate/Update Templated Report");
            NrkSdk.SetCollectionObjectNameArg("Report Template", "Position_2",
"ReportTemplate_Exp_PhD");
            NrkSdk.ExecuteStep();
            */

            NrkSdk.SetStep("Quick Report");
            NrkSdk.SetCollectionObjectNameArg("Item Name", "Position_3",
"Vector_Group_3");
            NrkSdk.SetStringArg("Report Name (optional)", "Vector_Group_Position_3");
            NrkSdk.SetBoolArg("Open Report?", true);
            NrkSdk.ExecuteStep();

            NrkSdk.SetStep("Output SA Report to PDF");
            NrkSdk.SetCollectionObjectNameArg("Report Name", "Position_3",
"Vector_Group_Position_3");
            NrkSdk.SetFilePathArg("File Name", "My_Report", false);
            NrkSdk.SetBoolArg("Show PDF?", true);
            NrkSdk.ExecuteStep();

        }
    }
}
```

Appendix B – Final List of Voice Commands Used in Unity

The final list of words used in Unity for the user to be able to interact with the ISLVM prototype is:

- Intro
- Run
- Connect
- Create Collection
- Add Instrument
- Start Instrument
- Locate Instrument
- Begin Location
- Begin Measuring
- Create Relationship
- Query Groups
- Generate Report
- Next
- Measure
- Best Fit

Appendix C – Paper Manual

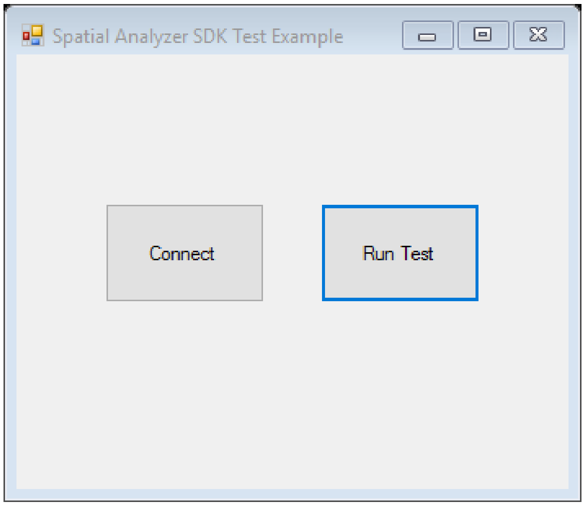
The paper manual that was used for Test 1 of the experimental validation of the ISLVM was the following:

Hello and welcome to this exciting trial! Today we will be attempting to be able to conduct a full measurement inspection of the assembly that you see on top of the granite bed. Let me explain a bit more on why we would like to do this.

As you might know, metrology is an area in engineering that deals with measurements. Yes measurements, not the weather forecast! Since measurements are one of the few ways we can know if something is correctly assembled or not it is very important in manufacturing. However it is not easy. So with the help of this script we will take you through the process of measuring an assembly with a Laser Tracker to see if we can help you and other operators perform a correct measurement of an assembly without having any previous experience with a Laser Tracker.

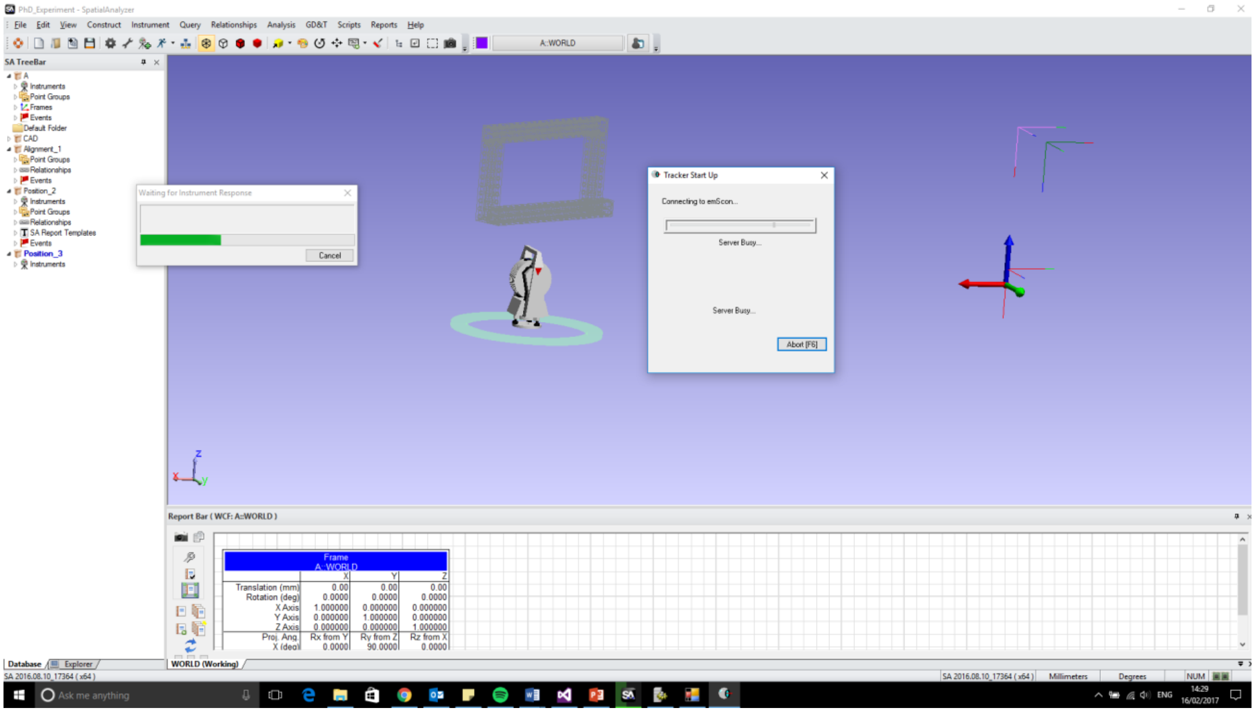
Today we will be using Spatial Analyzer (SA) to help us do the measurements of the assembly. SA is a 3D graphical software platform that integrates almost all of the metrology equipment available and helps us make measurements a lot easier and quicker. It is super cool! You will see it in action in just a couple of minutes! So let's get started!

1) On the screen of the laptop that has been provided you will see the following box:



Please click on the "Run Test" button.

2) This will now take you to the SA main screen and automatically the project that you will be working on today will be loaded for you and a Laser Tracker will be added for you in the environment. It is very important that while the Laser Tracker is being initialized that you **do not** cross the beam or interrupt the process in any way! You should see the following screen:



Waiting for Instrument Response

Tracker Start Up

Connecting to emScon...

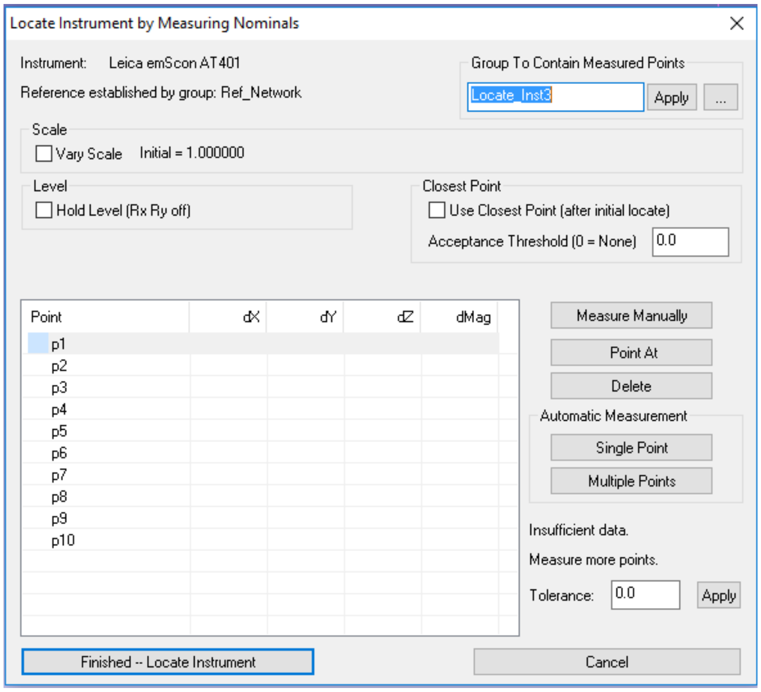
Server Busy...

Server Busy...

Report Bar (WCF: A::WORLD)

Frame A::WORLD	X	Y	Z
Translation (mm)	0.00	0.00	0.00
Rotation (deg)	0.0000	0.0000	0.0000
X Axis	1.000000	0.000000	0.000000
Y Axis	0.000000	1.000000	0.000000
Z Axis	0.000000	0.000000	1.000000
Proj. Ang.	Rx from Y	Ry from Z	Rz from X
X (deg)	0.0000	90.0000	0.0000

It might seem obvious to us where the Laser Tracker is in space, however SA has no idea of where the Laser Tracker is relative to our assembly object, nor our reference network. In order for it to know we need to do something that is called: "Locating the Instrument". Once we have located the instrument we can then proceed to take some measurements on the assembly. In order to do this we will first need to take 3 points. While you take these first 3 points it is ok for you to interrupt the beam path or lose the laser beam. This will not affect the measurements in any way, except if you interrupt it exactly when it is taking a measurement. After the laser tracker has finished initializing and has been added to the environment, on the screen you should be able to see the locating the instrument menu just like the following image:


Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

Insufficient data.

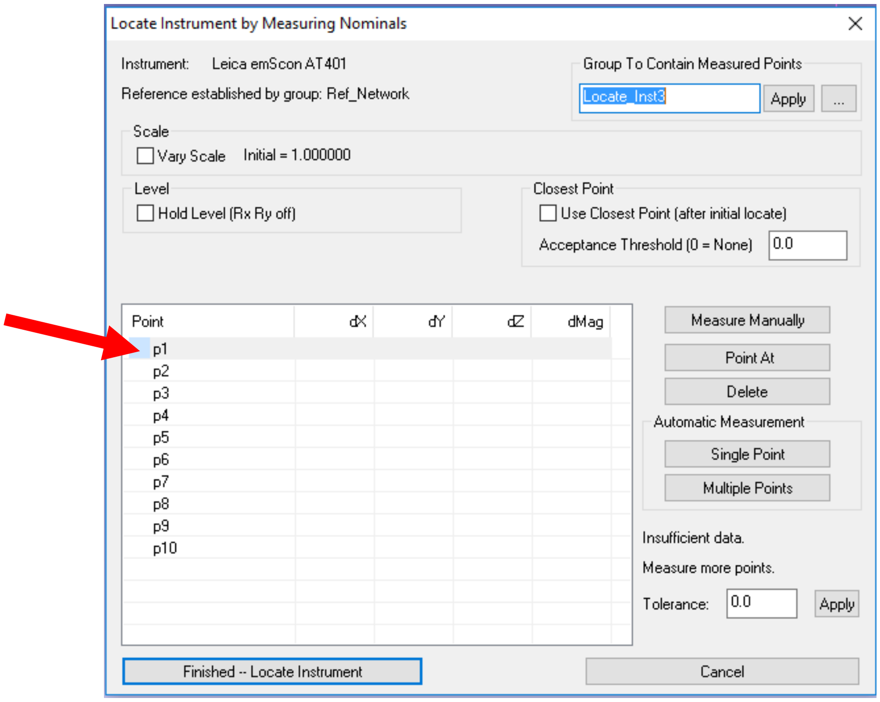
Measure more points.

Tolerance: 0.0

3) The next step is to take a measurement of our first point of the reference network. But before we proceed there is something that you need to know about SMRs which are an integral part to using the Laser Tracker. An SMR stands for Spherically Mounted Retro-reflector. Basically it is a very fancy mirror! If you look at the assembly jig you will see a metallic ball bearing with a hole into the ball in which you can see a mirror. This is the SMR. You can see a picture of it below:

There are different sizes of SMRs, if you look at the assembly jig again you will see 7 small SMR's glued to the granite bed and the table. The size depends on what you are using them for. In this case the small ones are used as part of a reference network and the big one will be used to take the measurements. An SMR is handled by grabbing it by the ball bearing. <u>**PLEASE NEVER, NEVER TOUCH THE GLASS!**</u> That is very important! If you walk over to the SMR you will be able to see that a laser point is being reflected back to the laser tracker. If you pick up the SMR and move it around with the mirror always facing the laser tracker you will be able to see how the laser tracker "tracks" the SMR and will move to where you move it. Once you have gotten familiar with this please place the SMR facing the laser tracker back on the black magnetic nest that is labelled #1 as it is shown in the following picture:

4) To take the measurement of our first reference point please head back to the laptop, and select the row labelled "p1" as shown in the image:



Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

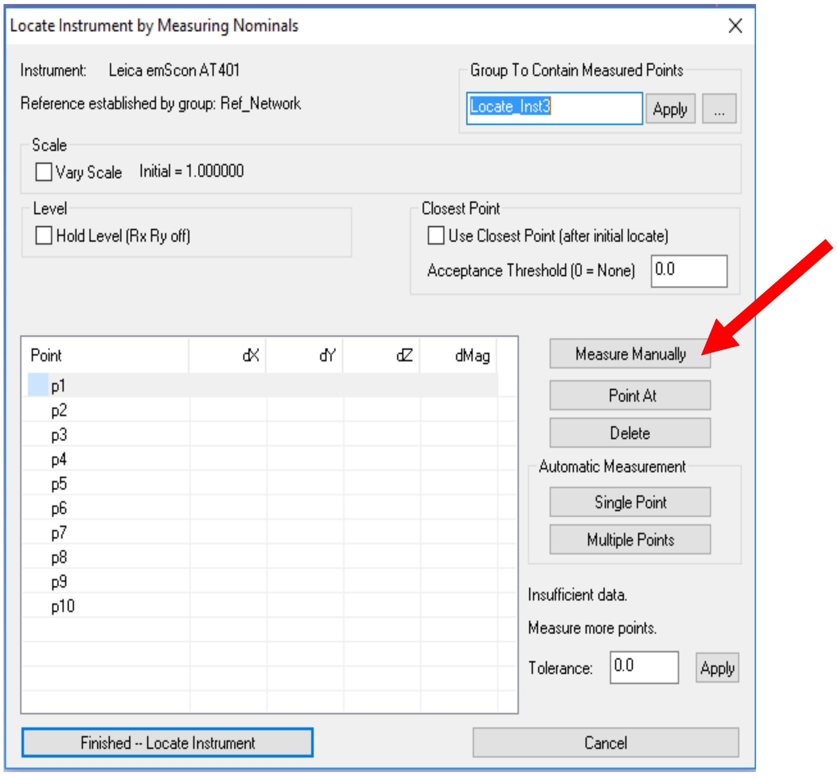
Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

Insufficient data.

Measure more points.

Tolerance: 0.0

Then please click the “Measure Manually” button that is located on the right side of the menu and signalled by the red arrow in the image below:



Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

☐ Vary Scale Initial = 1.000000

☐ Hold Level (Rx Ry off)

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

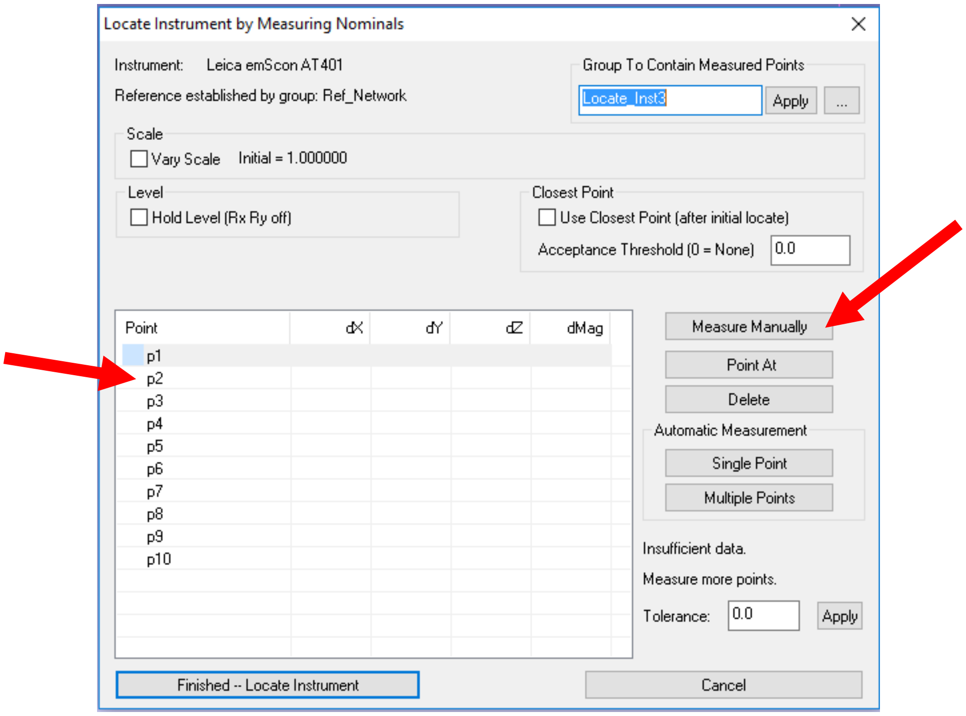
Insufficient data.

Measure more points.

Tolerance: 0.0

5) Now please pick up the SMR from nest #1 and place it on the nest that is labelled #2 with the mirror always facing the laser tracker as it is shown in the following picture:

Now please head back to the laptop, select the row labelled “p2” and click on the “Measure Manually button”.


Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None): 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

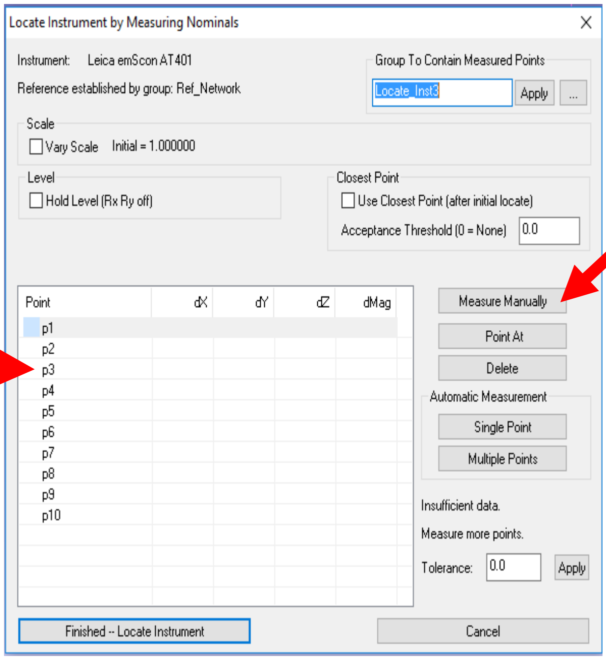
Insufficient data.

Measure more points.

Tolerance: 0.0

6) Finally please take the SMR from nest #2 and place it on the nest that is labelled #3 with the mirror facing the laser tracker as shown in the picture:

7) Then go back to the laptop, select the row labelled "p3" and click on the "Measure Manually" button.

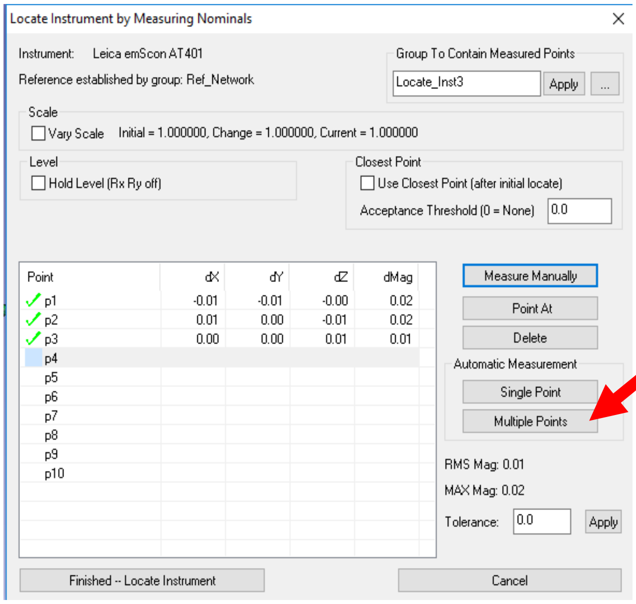


Instrument: Leica emScon AT401
Reference established by group: Ref_Network
Group To Contain Measured Points: Locate_Inst3
☐ Vary Scale Initial = 1.000000
☐ Hold Level (Rx Ry off)
☐ Use Closest Point (after initial locate)
Acceptance Threshold (0 = None) 0.0

p1
p2
p3
p4
p5
p6
p7
p8
p9
p10

Insufficient data.
Measure more points.
Tolerance: 0.0

8) With this SA now has a rough idea of where the tracker is and which reference network you are using. All we need to do now is take the rest of the points automatically. This will then tell SA to measure the 7 remaining points of our reference network. Then just watch how the Laser Tracker does this all by itself. In order to do this please click on the button on the right side of the menu that says "Multiple Points" under the Automatic Measurement section. You can see this button in the image below signalled by the red arrow. While these 7 points are being taken automatically please **do not** break the beam or interrupt the measurements in any way as this will cause errors in the measurements!

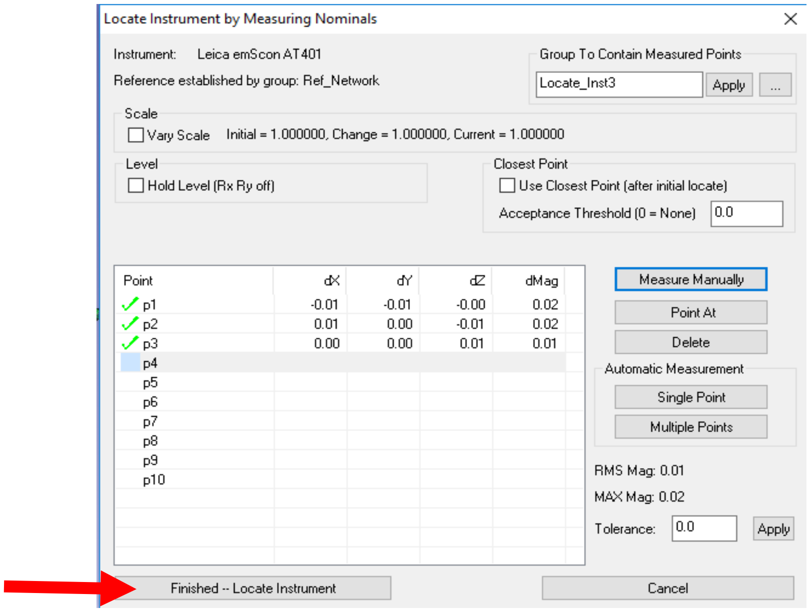


Instrument: Leica emScon AT401
Reference established by group: Ref_Network
Group To Contain Measured Points: Locate_Inst3
☐ Vary Scale Initial = 1.000000, Change = 1.000000, Current = 1.000000
☐ Hold Level (Rx Ry off)
☐ Use Closest Point (after initial locate)
Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
✓ p1	-0.01	-0.01	-0.00	0.02
✓ p2	0.01	0.00	-0.01	0.02
✓ p3	0.00	0.00	0.01	0.01
p4				
p5				
p6				
p7				
p8				
p9				
p10				

RMS Mag: 0.01
MAX Mag: 0.02
Tolerance: 0.0

9) Once the 7 remaining measurements have been taken finalize the location of the instrument by clicking on the “Finished- Locate Instrument” signalled with a red arrow in the image below.



Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000, Change = 1.000000, Current = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

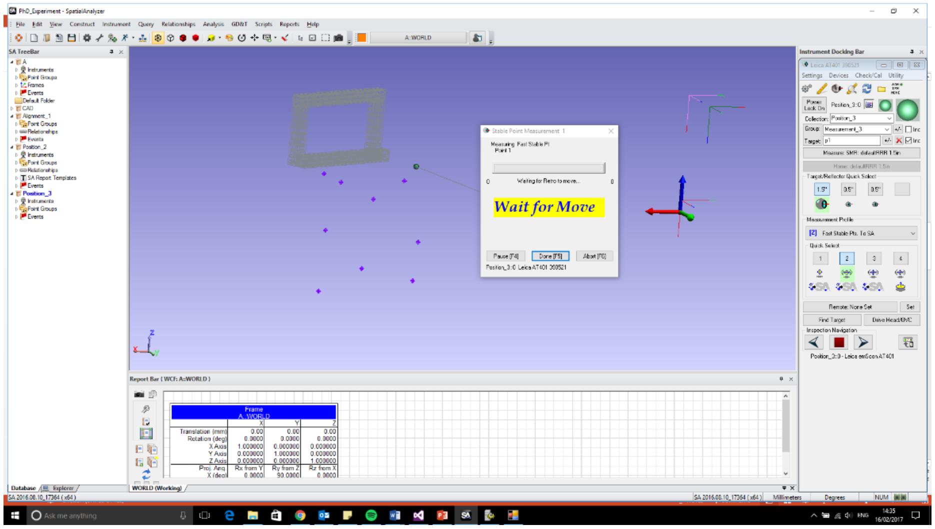
Point	dX	dY	dZ	dMag
✓ p1	-0.01	-0.01	-0.00	0.02
✓ p2	0.01	0.00	-0.01	0.02
✓ p3	0.00	0.00	0.01	0.01
p4				
p5				
p6				
p7				
p8				
p9				
p10				

RMS Mag: 0.01

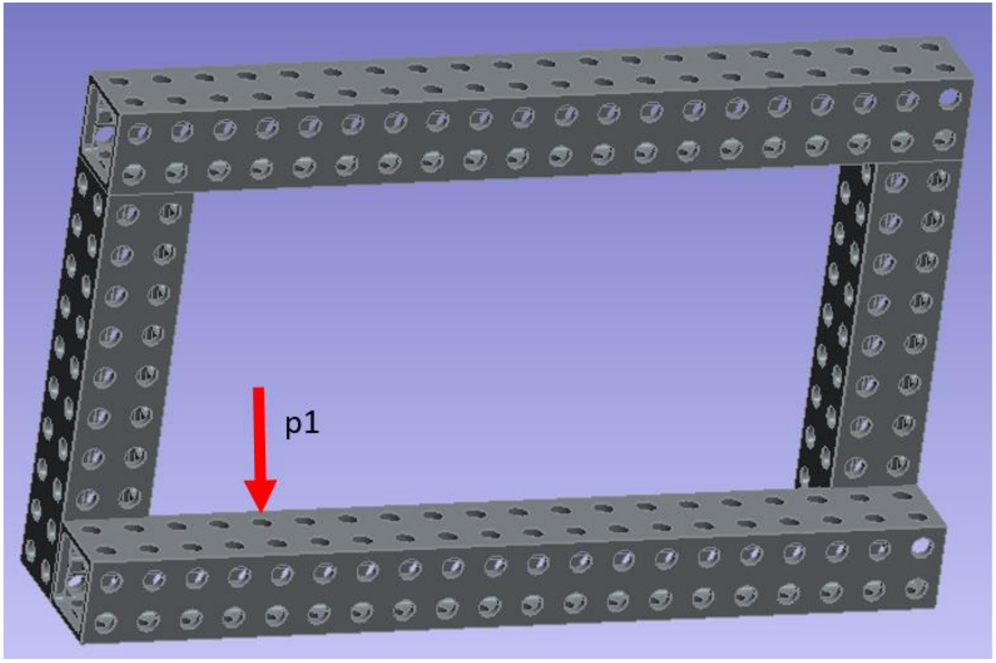
MAX Mag: 0.02

Tolerance: 0.0

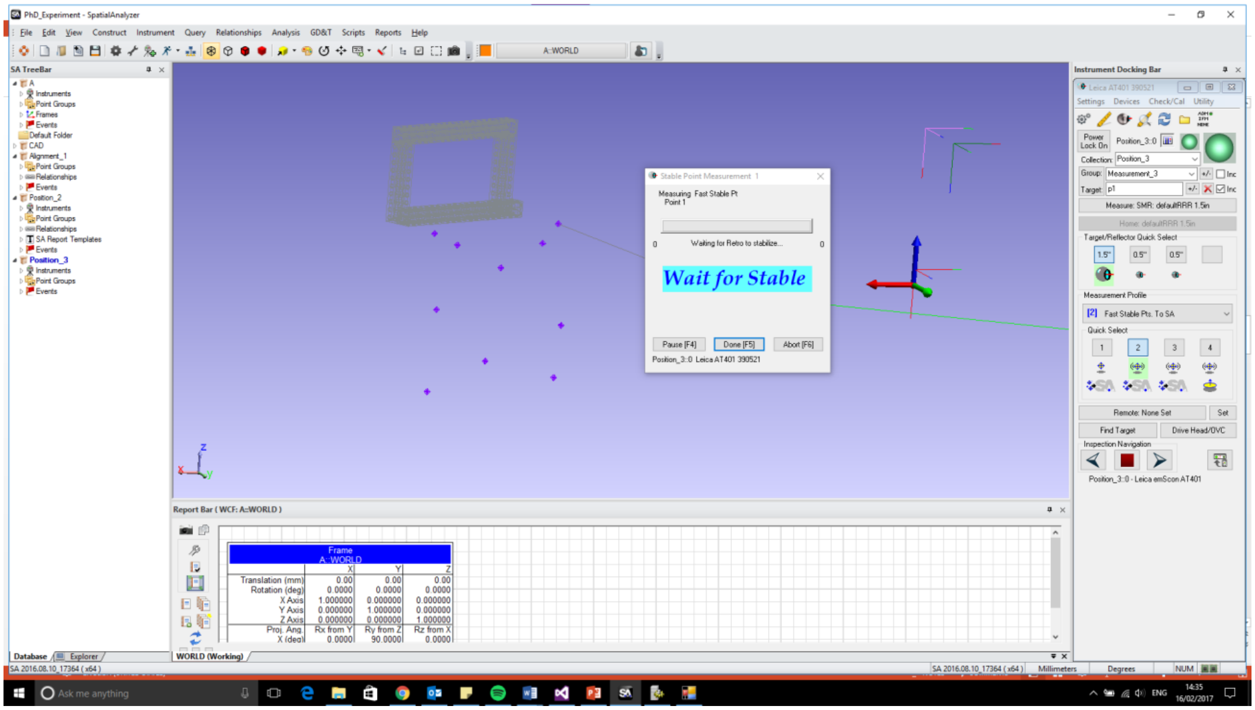
10) Immediately after clicking the “Finished- Locate Instrument” button SA will be ready to take measurements on the assembly component and it is very important for you to know that from this point onward until you finish measuring the assembly, **every time you break the beam, lose the beam or interrupt the laser beam in any way a measurement will then be taken.** Most likely is that it will be in a wrong position which will cause errors in the measurements! You should now see on your screen the following image:



11) For the assembly measurements we will take a total of 8 points. For these measurements please make sure that the SMR is in contact with the assembly at all times. Make sure the SMR is in one of the holes and do not position it just above, or just in front of it. The positions to be measured will be indicated by images with red arrows like the example below.



As soon as you start moving the SMR the measuring window in SA will change from a yellow "Wait to Move" to a light blue "Wait for Stable" message as can be seen in the image below:



Stable Point Measurement 1

Measuring Fast Stable Pt
Point 1

0 Waiting for Retro to stabilize... 0

Wait for Stable

Position_3::0 Leica AT401 390521

Position_3::0

Collection: Position_3

Group: Measurement_3 ☐ Inc

Target: p1 ☑ Inc

Measure: SMR: defaultRRR 1.5in

Home: defaultRRR 1.5in

Target/Reflector Quick Select: 1.5" 0.5" 0.5"

Measurement Profile: [2] Fast Stable Pts. To SA

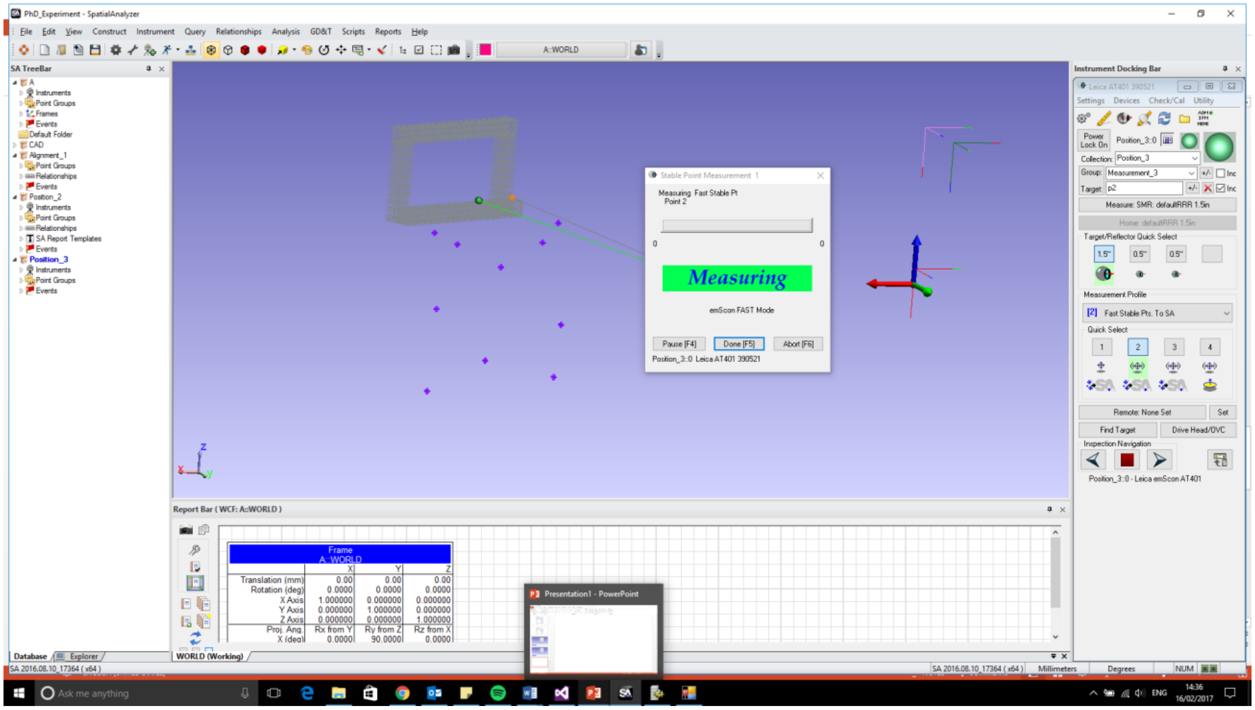
Quick Select: 1 2 3 4

Position_3::0 - Leica emScon AT401

Report Bar (WCF: A::WORLD)

Frame A::WORLD	X	Y	Z
Translation (mm)	0.00	0.00	0.00
Rotation (deg)	0.0000	0.0000	0.0000
X Axis	1.000000	0.000000	0.000000
Y Axis	0.000000	1.000000	0.000000
Z Axis	0.000000	0.000000	1.000000
Proj. Ang.	Rx from Y	Ry from Z	Rz from X
X (deg)	0.0000	90.0000	0.0000

This is perfectly normal and you can keep on moving the SMR all you want. However a measurement will not be taken until the SMR is completely still. Once the SMR is still there are two ways you can know that the Laser Tracker is measuring a point. The first one is that the measure window in SA will again change from the light blue “Wait for Stable” to a green “Measuring” message as can be seen in the following image:



Stable Point Measurement 1

Measuring Fast Stable Pt
Point 2

0 0

Measuring

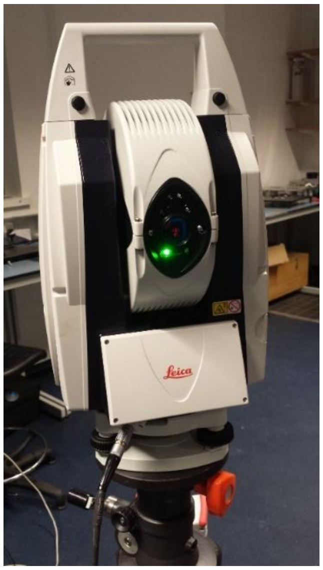
emScon FAST Mode

Pause [F4] Done [F5] Abort [F6]

Position_3::0 Leica AT401 390521

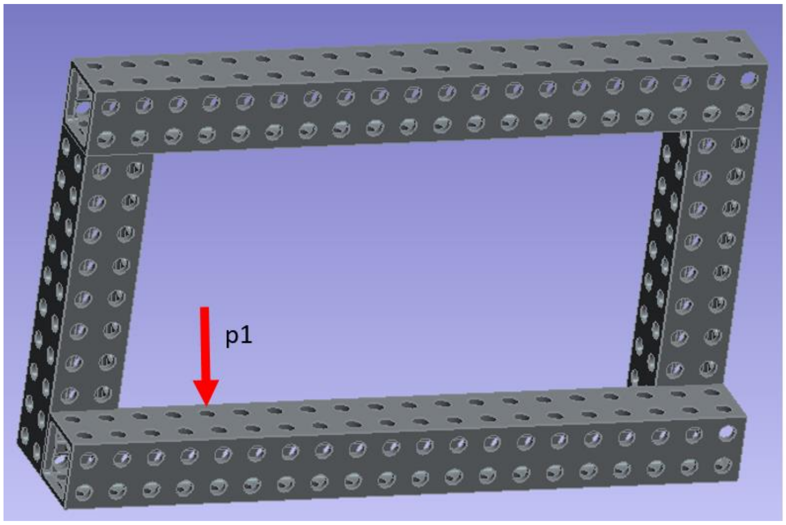
Frame A::WORLD	X	Y	Z
Translation (mm)	0.00	0.00	0.00
Rotation (deg)	0.0000	0.0000	0.0000
X Axis	1.000000	0.000000	0.000000
Y Axis	0.000000	1.000000	0.000000
Z Axis	0.000000	0.000000	1.000000
Proj. Ang.	Rx from Y	Ry from Z	Rz from X
X (deg)	0.0000	90.0000	0.0000

The second way you can know that the laser tracker is taking a measurement is that in the front part of the Laser Tracker you will be able to see a green LED like the image below:

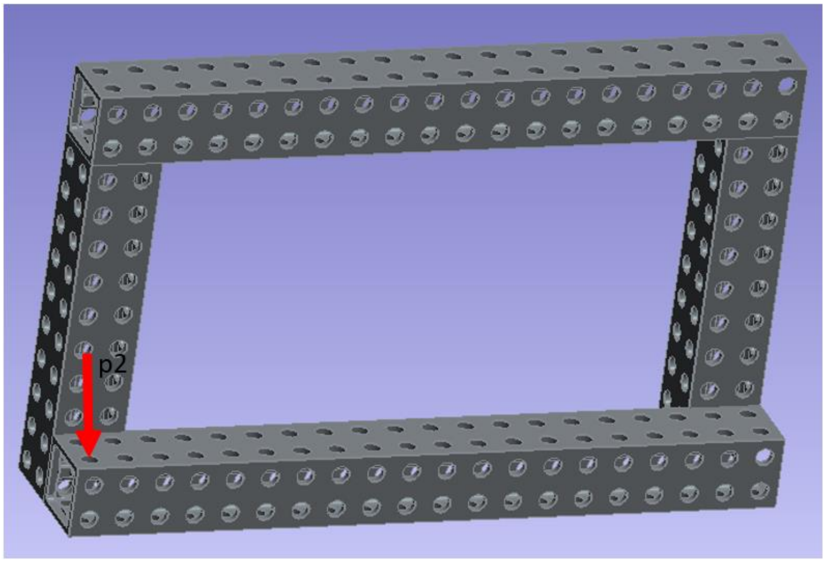


As soon as the laser tracker starts to take a measurement this green LED will start blinking. You will know that the measurement has finished when this green LED is no longer blinking, when the measurement window in SA turns from the green “Measuring” to the yellow

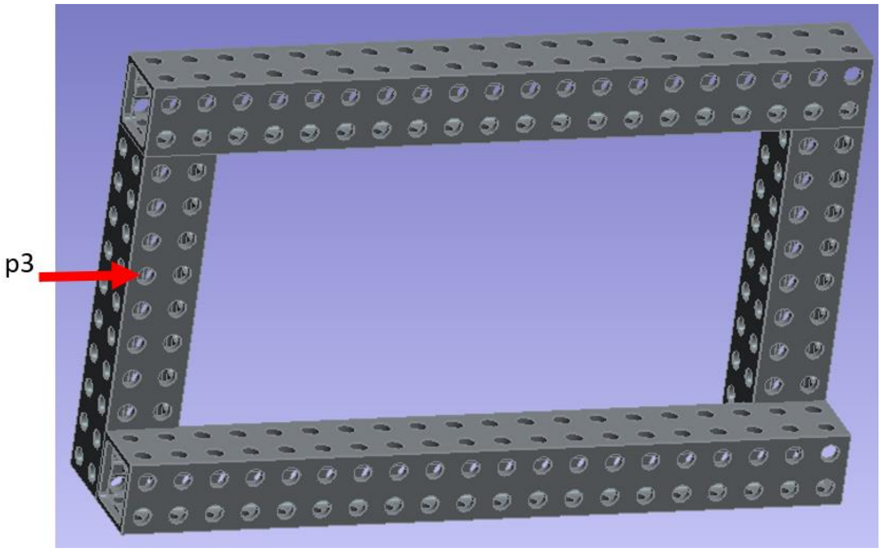
"Wait for Move" message, or you will hear a beep sound that the computer will make once the measurement has been completed. These three indicators will always happen and try to be aware of them so you can be certain of when a measurement has been taken.
With all this in mind please proceed to take the measurements. Before you take the first point please go to the assembly, and grab the SMR from the nest labelled #3. Then place the SMR in-front of the small SMR labelled # 10 which the laser tracker is currently pointing at. This will "re-capture" the laser point and the laser tracker will now track the big SMR. Once you have achieved this please place the SMR at the first point signalled by the red arrow in the following picture:



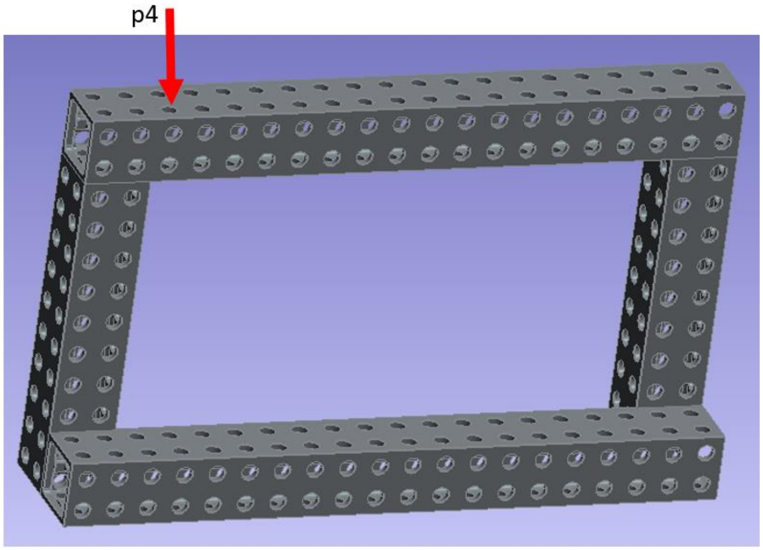
12) Once you have taken the measurement for point #1 of the assembly please place the SMR on position #2 indicated by the picture below:



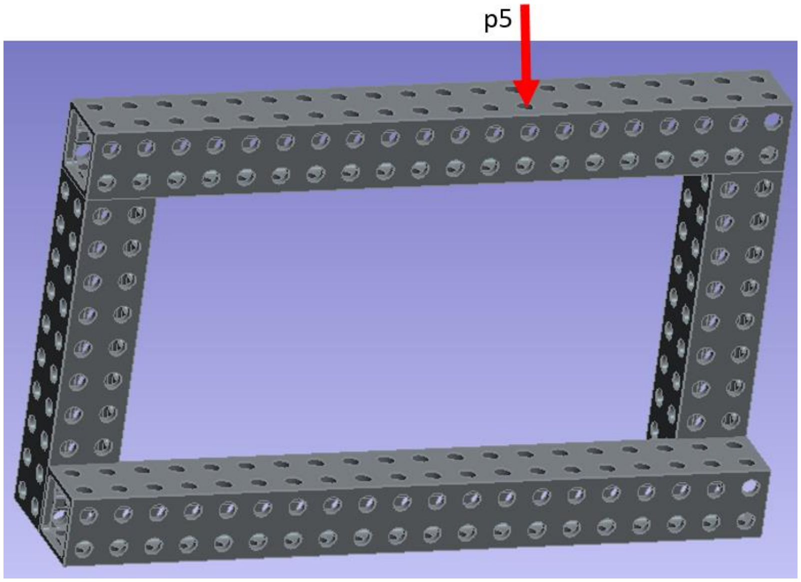
13) After the measurement for position #2 has been taken, place the SMR in position #3. For this point please make sure that you are always holding on to the SMR! There is no nest and it won't stick to the vertical column of the assembly. Hence do not let go of the SMR throughout the measurement. Position #3 is indicated by the image below:



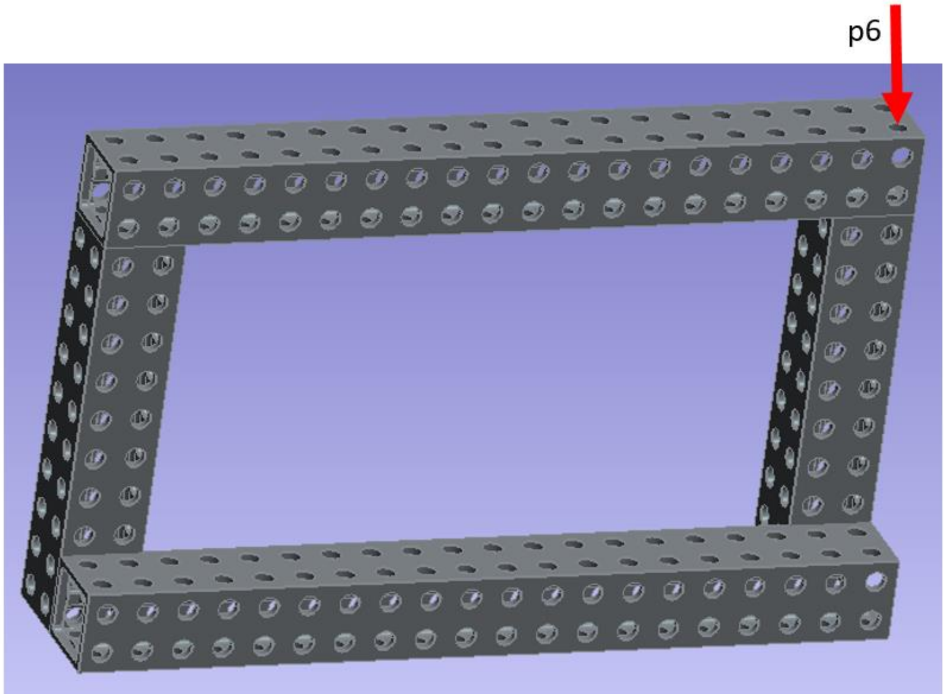
14) Once you have completed the measurement take the SMR to position #4 indicated by the image below:



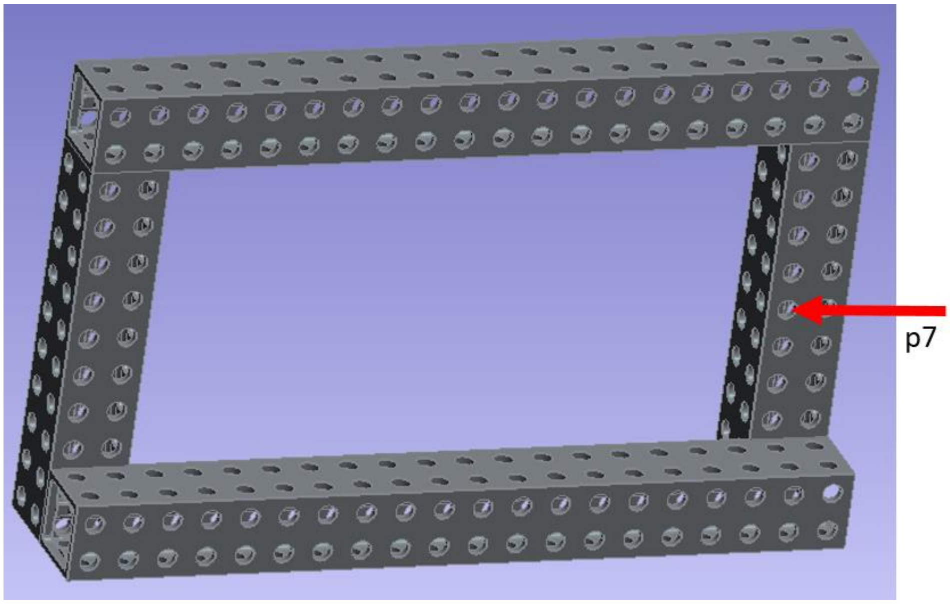
15) After you have completed measurement # 4 please place the SMR at position # 5 indicated by the following image:



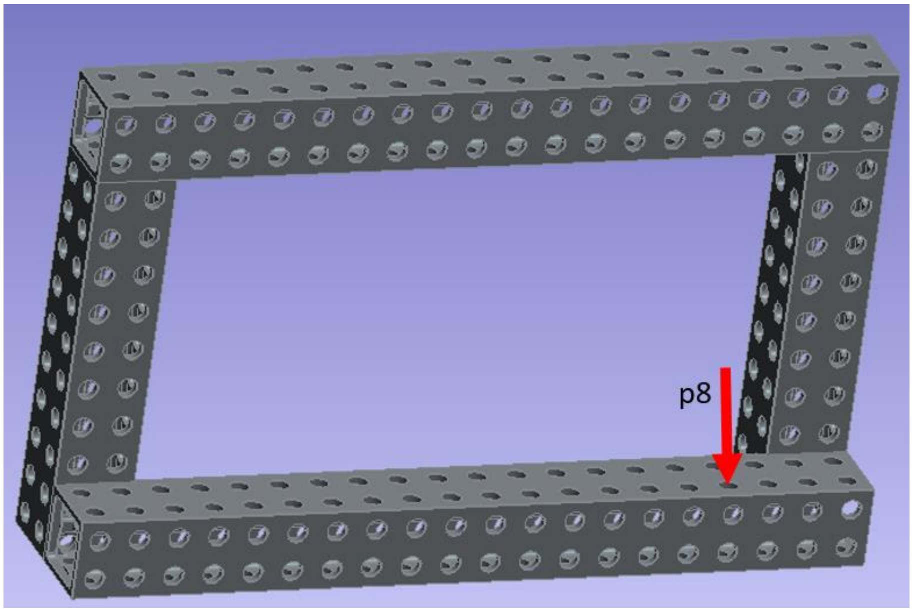
16) After you have completed measurement # 5 please place the SMR at position #6 indicated by the following image:



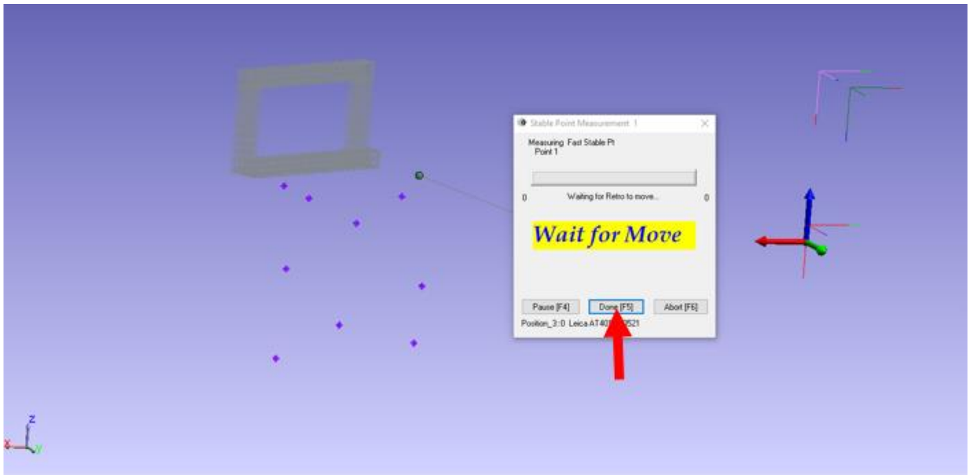
17) Once you have completed measurement #6 please place the SMR at position # 7. Just as position #3 please hold the SMR at all times and do not let go of it throughout the measurement. The SMR will not stick to the vertical column of the assembly! Position #7 is indicated by the figure below:



18) Finally after you have completed measurement # 7 please place the SMR at position #8 indicated by the following image:



19) In order to complete the measurements, please click on the “Done” button of the measurement window in SA indicated by the following image:



Measuring Fast Stable Pt
Point 1

0 Waiting for Retro to move... 0

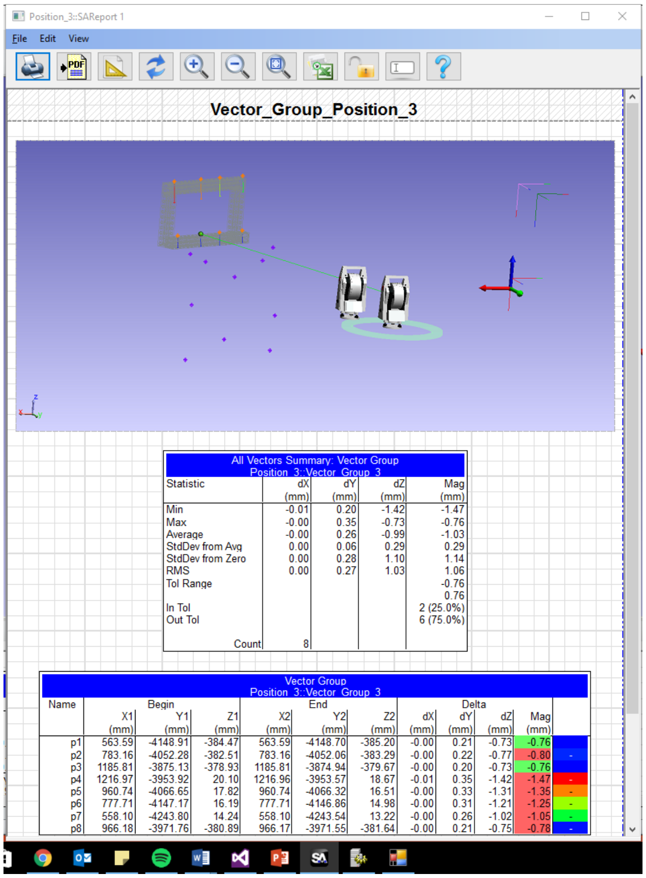
Wait for Move

Position_3::0 Leica AT40

20) Immediately after you have clicked the “Done” button a series of steps will automatically happen in SA and most likely you won’t be able to notice what it is that SA is doing. The following is a brief explanation of what SA automatically did:

- First SA created a relationship between the 8 measured points and the assembly object. This is necessary because although we have located our instrument in space SA still doesn’t know to whom these measurements belong to. By creating a relationship we are telling SA that those 8 measured points and the assembly go together!
- Unfortunately there is never a perfect measurement in large volume metrology and there is always room for improvement! So in order to reduce these small errors in the measurements SA has a very nice command that takes the relationship previously defined and best fits the points measured to the assembly. That is what SA executed automatically after creating the relationship.
- Now that the measured points and the assembly are close together we would like to know the deviations between our assembly and the nominal values. Our assembly is represented by the measured points in SA and the nominal values is the CAD drawing of the assembly that you have been seeing in SA. By performing this comparison is how we can know if our assembly meets the required specifications or not. This is what SA did after best fitting the points to the assembly. You will see these deviations plotted in SA by colour arrow vectors that come out of the measured points. The colour of these arrows is directly related to the deviations.

21) If you did everything correctly you will be able to see in SA the final report of the measurements. In the report you should be able to see a picture that contains the assembly, the laser tracker, the points of the reference network, the 8 points measured on the assembly and out of each of the 8 measured points you should see the vector arrows that represent the deviations of the measurements. Below this picture you should have two tables with all the data of these vectors. The report should look similar to the following image:



Vector_Group_Position_3

All Vectors Summary: Vector Group Position 3::Vector Group 3				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.01	0.20	-1.42	-1.47
Max	-0.00	0.35	-0.73	-0.76
Average	-0.00	0.26	-0.99	-1.03
StdDev from Avg	0.00	0.06	0.29	0.29
StdDev from Zero	0.00	0.28	1.10	1.14
RMS	0.00	0.27	1.03	1.06
Tol Range				-0.76 0.76
In Tol				2 (25.0%)
Out Tol				6 (75.0%)
Count	8			

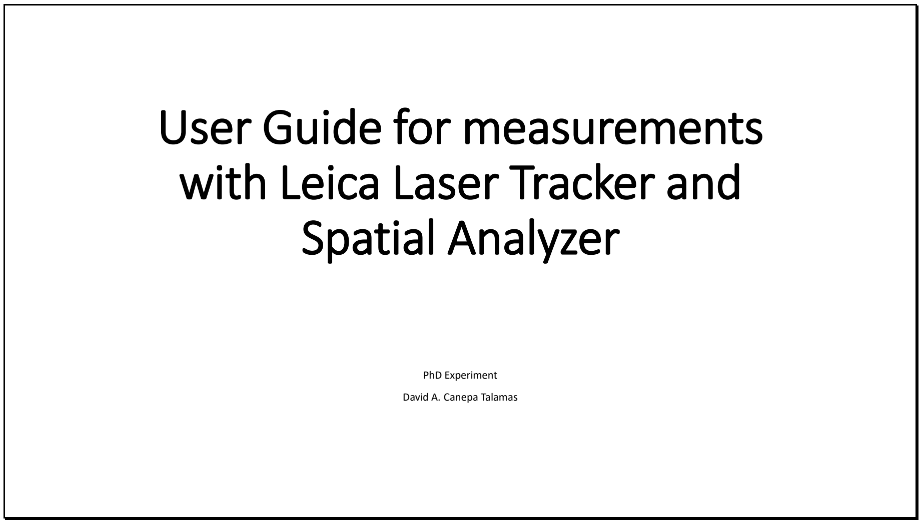
Vector Group Position 3::Vector Group 3											
Name	Begin			End			Delta				
	X1 (mm)	Y1 (mm)	Z1 (mm)	X2 (mm)	Y2 (mm)	Z2 (mm)	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)	
p1	563.59	-4148.91	-384.47	563.59	-4148.70	-385.20	-0.00	0.21	-0.73	-0.76	
p2	783.16	-4052.28	-382.51	783.16	-4052.06	-383.29	-0.00	0.22	-0.77	-0.80	-
p3	1185.81	-3875.13	-378.93	1185.81	-3874.94	-379.67	-0.00	0.20	-0.73	-0.76	
p4	1216.97	-3953.92	20.10	1216.96	-3953.57	18.67	-0.01	0.35	-1.42	-1.47	-
p5	960.74	-4066.65	17.82	960.74	-4066.32	16.51	-0.00	0.33	-1.31	-1.35	-
p6	777.71	-4147.17	16.19	777.71	-4146.86	14.98	-0.00	0.31	-1.21	-1.25	-
p7	558.10	-4243.80	14.24	558.10	-4243.54	13.22	-0.00	0.26	-1.02	-1.05	-
p8	966.18	-3971.76	-380.89	966.17	-3971.55	-381.64	-0.00	0.21	-0.75	-0.78	-

With this you have now completed a full measurement inspection with the laser tracker! You should be proud of yourself as this is no easy task. Thank you very much for your time and patience! We hope that you have a great day!

Appendix D – Digital Manual Used with the Laptop

The digital manual used in the laptop to guide the volunteers through Test 2 of the experimental validation of the ISLVM was the following:

Slide 1

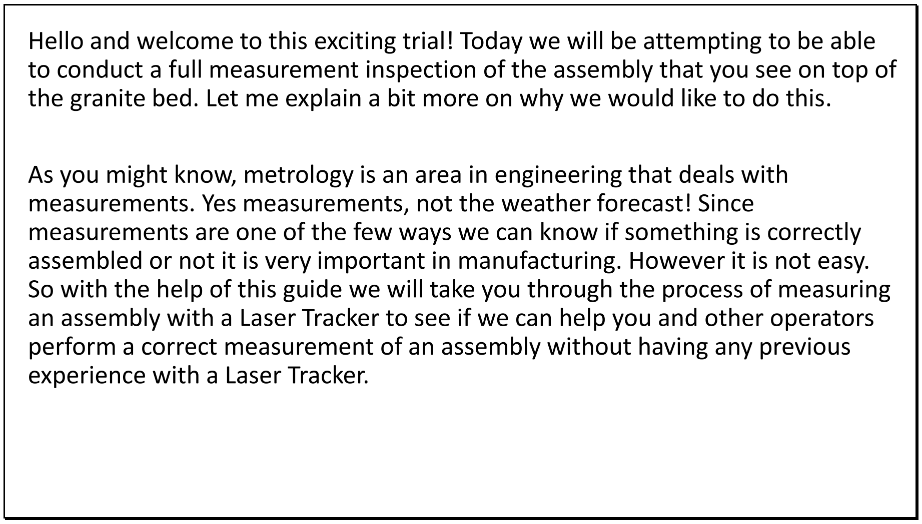


User Guide for measurements with Leica Laser Tracker and Spatial Analyzer

PhD Experiment

David A. Canepa Talamas

Slide 2



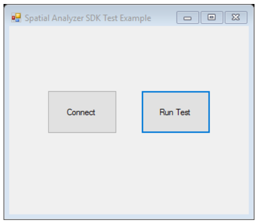
Hello and welcome to this exciting trial! Today we will be attempting to be able to conduct a full measurement inspection of the assembly that you see on top of the granite bed. Let me explain a bit more on why we would like to do this.

As you might know, metrology is an area in engineering that deals with measurements. Yes measurements, not the weather forecast! Since measurements are one of the few ways we can know if something is correctly assembled or not it is very important in manufacturing. However it is not easy. So with the help of this guide we will take you through the process of measuring an assembly with a Laser Tracker to see if we can help you and other operators perform a correct measurement of an assembly without having any previous experience with a Laser Tracker.

Slide 3

Today we will be using Spatial Analyzer (SA) to help us do the measurements of the assembly. SA is a 3D graphical software platform that integrates almost all of the metrology equipment available and helps us make measurements a lot easier and quicker. It is super cool! You will see it in action in just a couple of minutes! So let's get started!

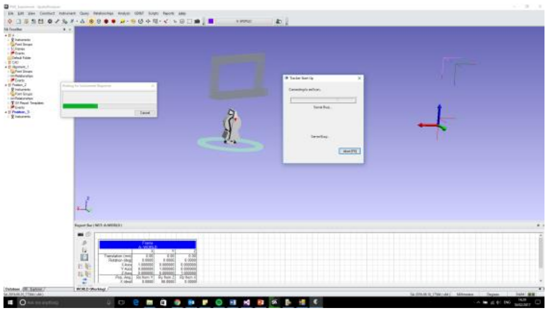
1. On the screen of the laptop that has been provided you will see the following box:



Please click on the "Run Test" button.

Slide 4

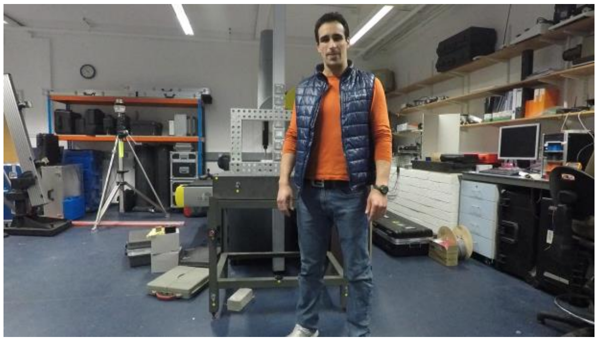
2. This will now take you to the SA main screen and automatically the project that you will be working on today will be loaded for you and a Laser Tracker will be added for you in the environment. It is very important that while the Laser Tracker is being initialized that you **do not** cross the beam or interrupt the process in any way! You should see the following screen:



Slide 5

The next step is to take a measurement of our first point of the reference network. But before we proceed there is something that you need to know about SMRs which are an integral part to using the Laser Tracker.

Please play the video below:



Slide 6

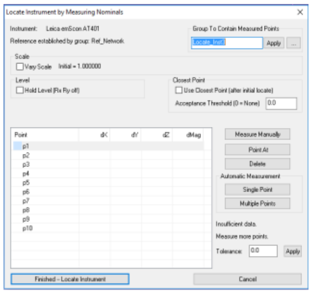
Please play the following video:

Slide 7

Once you have gotten familiar with the SMR please place it back on the black magnetic nest that is labelled #1 facing the laser tracker as it is shown in the following picture:

Slide 8

After the laser tracker has finished initializing and has been added to the environment, on the screen you should be able to see the locating the instrument menu just like the following image:


Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

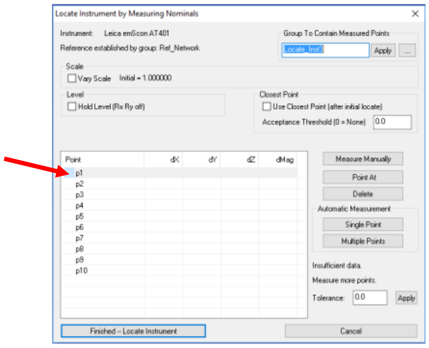
Insufficient data.

Measure more points.

Tolerance: 0.0

Slide 9

While you take these first 3 points it is ok for you to interrupt the beam path or lose the laser beam. This will not affect the measurements in any way, except if you interrupt it exactly when it is taking a measurement. To take the measurement of our first reference point please head back to the laptop, and select the row labelled “p1” as shown in the image:


Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale: ☐ Vary Scale Initial = 1.000000

Level: ☐ Hold Level (Rx Ry off)

Closest Point: ☐ Use Closest Point (after initial locate)

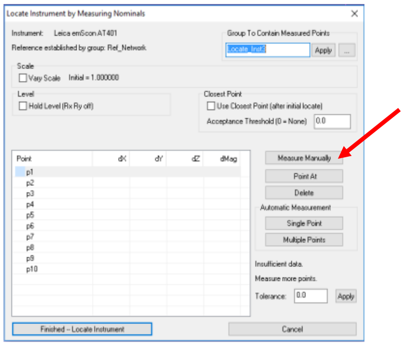
Acceptance Threshold (0 = None): 0.0

Insufficient data.
Measure more points.

Tolerance: 0.0

Slide 10

Then please click the “Measure Manually” button that is located on the right side of the menu and signalled by the red arrow in the image below:


Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale: ☐ Vary Scale Initial = 1.000000

Level: ☐ Hold Level (Rx Ry off)

Closest Point: ☐ Use Closest Point (after initial locate)

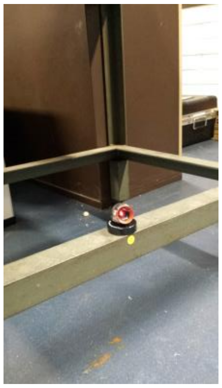
Acceptance Threshold (0 = None): 0.0

Insufficient data.
Measure more points.

Tolerance: 0.0

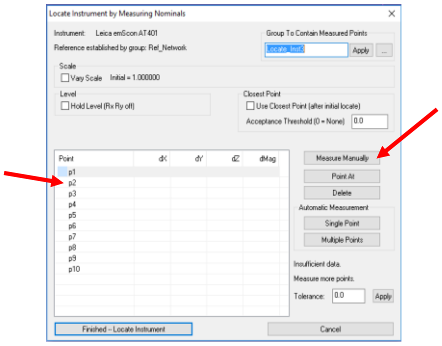
Slide 11

3. Now please pick up the SMR from nest #1 and place it on the nest that is labelled #2 with the mirror always facing the laser tracker as it is shown in the following picture:



Slide 12

Now please head back to the laptop, select the row labelled “p2” and click on the “Measure Manually button”



Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

Insufficient data.

Measure more points.

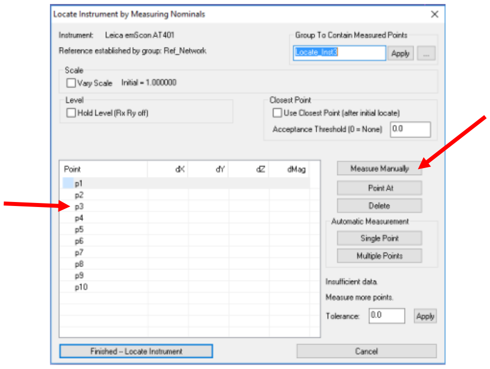
Tolerance: 0.0

Slide 13

4. Finally please take the SMR from nest #2 and place it on the nest that is labelled #3 with the mirror facing the laser tracker as shown in the picture:

Slide 14

Then go back to the laptop, select the row labelled “p3” and click on the “Measure Manually” button.



Locate Instrument by Measuring Nominals

Instrument: Leica emScon AT401

Reference established by group: Ref_Network

Group To Contain Measured Points: Locate_Inst3

Scale

☐ Vary Scale Initial = 1.000000

Level

☐ Hold Level (Rx Ry off)

Closest Point

☐ Use Closest Point (after initial locate)

Acceptance Threshold (0 = None) 0.0

Point	dX	dY	dZ	dMag
p1				
p2				
p3				
p4				
p5				
p6				
p7				
p8				
p9				
p10				

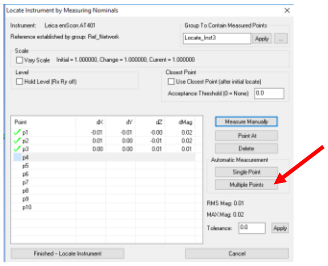
Insufficient data.

Measure more points.

Tolerance: 0.0

Slide 15

5. All we need to do now is take the rest of the points automatically. Then just watch how the Laser Tracker does this all by itself. In order to do this please click on the button on the right side of the menu that says “Multiple Points” under the Automatic Measurement section. You can see this button in the image below signalled by the red arrow. While these 7 points are being taken automatically please **do not** break the beam or interrupt the measurements in any way as this will cause errors in the measurements!



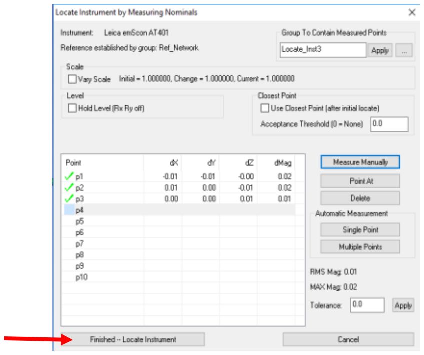
Instrument: Leica emScon AT401
Reference established by group: Ref_Network
Group To Contain Measured Points: Locate_Inst3
☐ Vary Scale Initial = 1.000000, Change = 1.000000, Current = 1.000000
☐ Hold Level (Rx Ry off)
☐ Use Closest Point (after initial locate)
Acceptance Threshold (0 = None): 0.0

Point	dX	dY	dZ	dMag
✓ p1	-0.01	-0.01	-0.00	0.02
✓ p2	0.01	0.00	-0.01	0.02
✓ p3	0.00	0.00	0.01	0.01
p4				
p5				
p6				
p7				
p8				
p9				
p10				

RMS Mag: 0.01
MAX Mag: 0.02
Tolerance: 0.0

Slide 16

6. Once the 7 remaining measurements have been taken finalize the location of the instrument by clicking on the “Finished- Locate Instrument” signalled with a red arrow in the image below.



Instrument: Leica emScon AT401
Reference established by group: Ref_Network
Group To Contain Measured Points: Locate_Inst3
☐ Vary Scale Initial = 1.000000, Change = 1.000000, Current = 1.000000
☐ Hold Level (Rx Ry off)
☐ Use Closest Point (after initial locate)
Acceptance Threshold (0 = None): 0.0

Point	dX	dY	dZ	dMag
✓ p1	-0.01	-0.01	-0.00	0.02
✓ p2	0.01	0.00	-0.01	0.02
✓ p3	0.00	0.00	0.01	0.01
p4				
p5				
p6				
p7				
p8				
p9				
p10				

RMS Mag: 0.01
MAX Mag: 0.02
Tolerance: 0.0

Slide 17

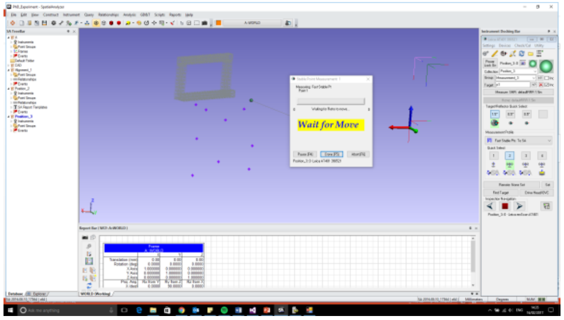
Immediately after clicking the “Finished- Locate Instrument” button SA will be ready to take measurements on the assembly component and it is very important for you to know that from this point onward until you finish measuring the assembly, **every time you break the beam, lose the beam or interrupt the laser beam in any way a measurement will then be taken.** Most likely is that it will be in a wrong position which will cause errors in the measurements!

Slide 18

Please play the video below:

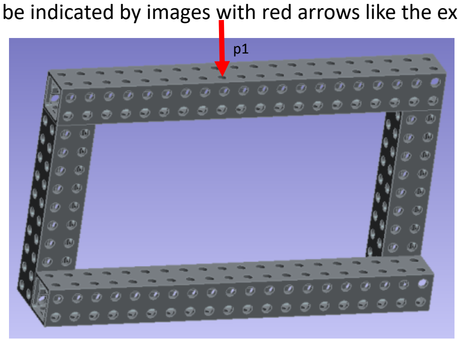
Slide 19

7. SA is now ready to take measurements on the assembly component and you should now see on the screen the following image



Slide 20

For the assembly measurements we will take a total of 8 points. For these measurements please make sure that the SMR is in contact with the assembly at all times. Make sure the SMR is in one of the holes and do not position it just above, or just in front of it. The positions to be measured will be indicated by images with red arrows like the example below.



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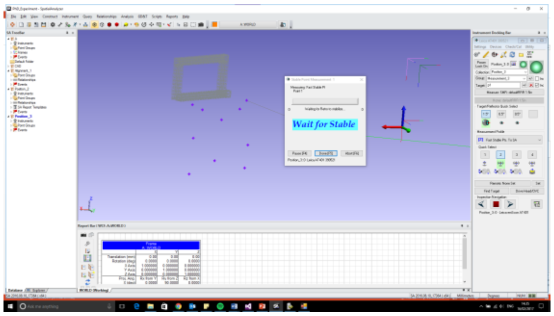
As soon as you start moving the SMR the measuring window in SA will change from a yellow “Wait to Move” to a light blue “Wait for Stable” message as can be seen in the image below:



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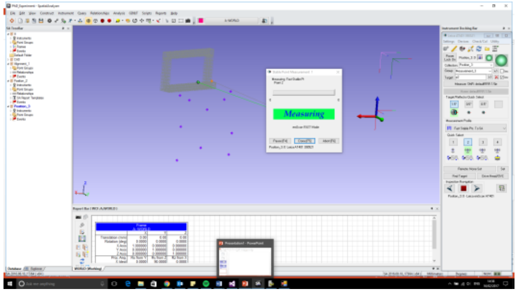
This is perfectly normal and you can keep on moving the SMR all you want. However a measurement will not be taken until the SMR is completely still. Once the SMR is still there are two ways you can know that the Laser Tracker is measuring a point. The first one is that the measure window in SA will again change from the light blue “Wait for Stable” to a green “Measuring” message as can be seen in the following image:



Slide 23

The second way you can know that the laser tracker is taking a measurement is that in the front part of the Laser Tracker you will be able to see a green LED like the image below:

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As soon as the laser tracker starts to take a measurement this green LED will start blinking. You will know that the measurement has finished when this green LED is no longer blinking, when the measurement window in SA turns from the green “Measuring” to the yellow “Wait for Move” message, or you will hear a beep sound that the computer will make once the measurement has been completed. All of these three indicators will always happen and try to be aware of them so you can be certain of when a measurement has been taken.

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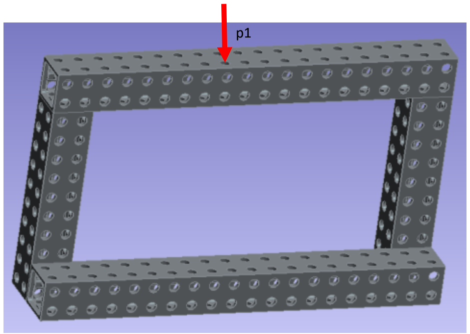
With all this in mind please proceed to “re-capture” the laser with the big SMR to be able to take the measurement of the first point. Point #1 is shown by the red arrow in the following image:



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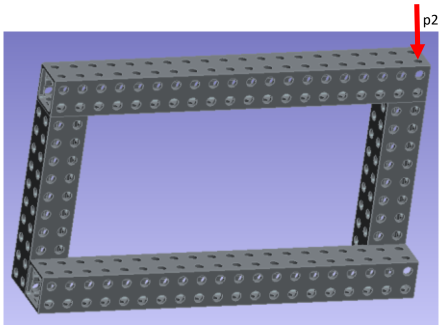
8. Once you have taken the measurement for point 1 of the assembly please place the SMR on position #2 indicated by the picture below:



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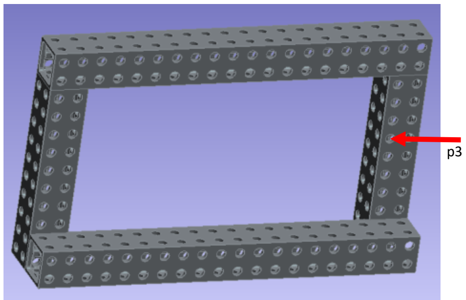
9. After the measurement for position #2 has been taken, place the SMR in position #3. For this point please make sure that you are always holding on to the SMR! There is no nest and it won’t stick to the vertical column of the assembly. Hence do not let go of the SMR throughout the measurement. Position #3 is indicated by the image below:



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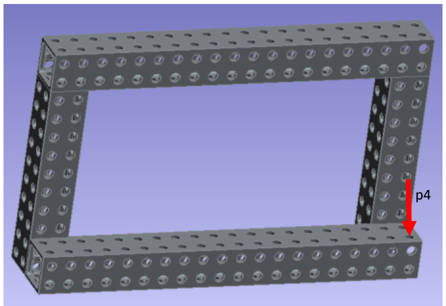
10. Once you have completed the measurement take the SMR to position #4 indicated by the image below:



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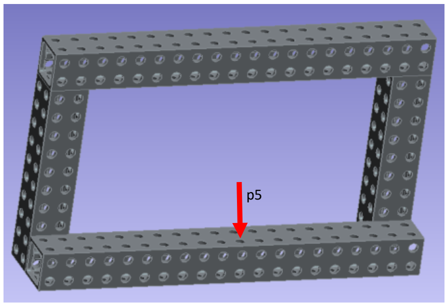
11. After you have completed measurement # 4 please place the SMR at position # 5 indicated by the following image:



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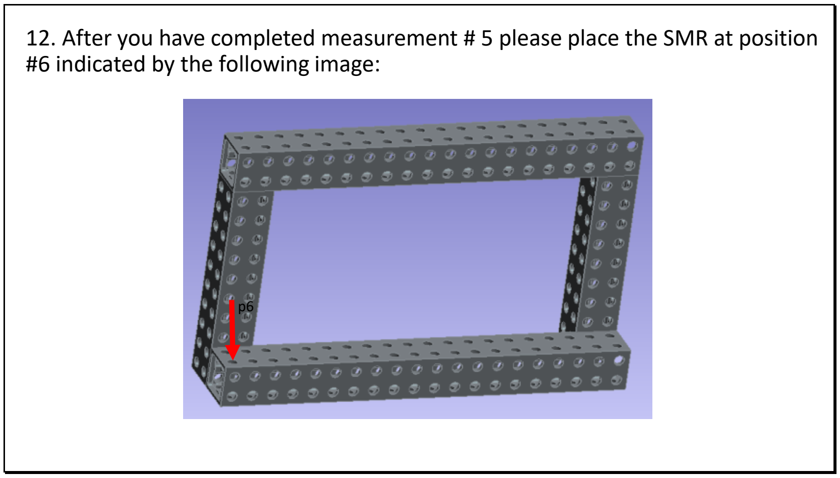

12. After you have completed measurement # 5 please place the SMR at position #6 indicated by the following image:

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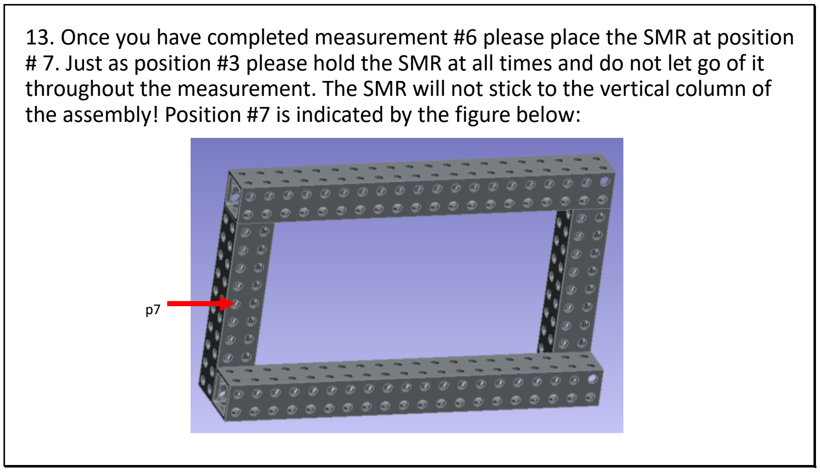

13. Once you have completed measurement #6 please place the SMR at position # 7. Just as position #3 please hold the SMR at all times and do not let go of it throughout the measurement. The SMR will not stick to the vertical column of the assembly! Position #7 is indicated by the figure below:

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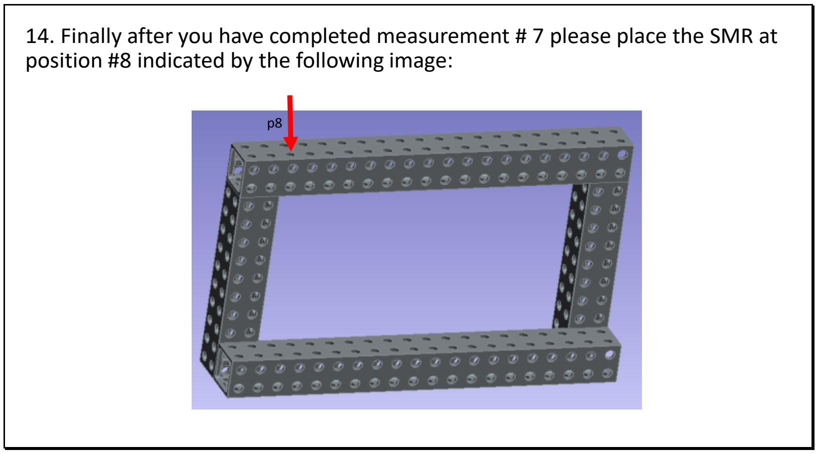

14. Finally after you have completed measurement # 7 please place the SMR at position #8 indicated by the following image:

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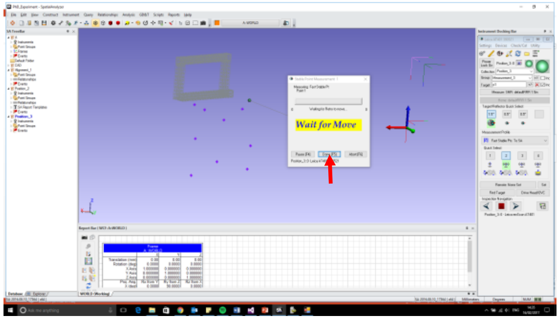
15. In order to complete the measurements, please click on the “Done” button of the measurement window in SA indicated by the following image:



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16. Immediately after you have clicked the “Done” button a series of steps will automatically happen in SA and most likely you won’t be able to notice what it is that SA is doing. The following is a brief explanation of what SA automatically did:

- First SA created a relationship between the 8 measured points and the assembly object. This is necessary because although we have located our instrument in space SA still doesn’t know to whom these measurements belong to. By creating a relationship we are telling SA that those 8 measured points and the assembly go together!
- Unfortunately there is never a perfect measurement in large volume metrology and there is always room for improvement! So in order to reduce these small errors in the measurements SA has a very nice command that takes the relationship previously defined and best fits the points measured to the assembly. That is what SA executed automatically after creating the relationship.
- Now that the measured points and the assembly are close together we would like to know the deviations between our assembly and the nominal values. Our assembly is represented by the measured points in SA and the nominal values is the CAD drawing of the assembly that you have been seeing in SA. By performing this comparison is how we can know if our assembly meets the required specifications or not. This is what SA did after best fitting the points to the assembly. You will see these deviations plotted in SA by colour arrow vectors that come out of the measured points. The colour of these arrows is directly related to the deviations.

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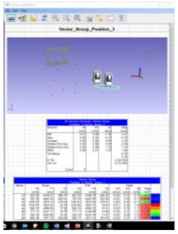
17. If you did everything correctly you will be able to see in SA the final report of the measurements. In the report you should be able to see a picture that contains the assembly, the laser tracker, the points of the reference network, the 8 points measured on the assembly and out of each of the 8 measured points you should see the vector arrows that represent the deviations of the measurements. Below this picture you should have two tables with all the data of these vectors. The report should look similar to the following image:



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With this you have now completed a full measurement inspection with the laser tracker! You should be proud of yourself as this is no easy task.

Thank you very much for your time and patience!

We hope that you have a great day!

Appendix E – Statistics Model used in R

The model used in R to calculate the statistics from the data gathered is the following (This model was designed by Dr. Horacio Muñoz):

```
### Dataset
setwd("~/David")
dat<-read.csv("data_9_parameters.csv")

#dat <- copypaste::ctrl_v()

dat$interface <- as.factor(dat$interface)

# Bayesian approach
library(MCMCpack)
library(dplyr)
library(tidyr)

fit2<-MCMChpoisson(fixed=errors~interface-1,
          random=~1,
          group="participant",
          data=dat,
          burnin=5000,mcmc=100000,thin=10,verbose=1,seed=27,
          mubeta=0,Vbeta=1e+03,r=1,R=0.01,
          nu=0.001,delta=0.001)

# We just want to check if these are statistically significant.
dat %>% select(errors) %>% aggregate(list(dat$interface),mean)
```

```
# Table with results
res <- data.frame(interface = 1:3,
                Mean = (fit2$lambda.pred %>% aggregate(list(dat$interface),mean))$x,
                LB = (fit2$lambda.pred %>%
aggregate(list(dat$interface),function(x){return(quantile(x,0.025))}))$x,
                UB = (fit2$lambda.pred %>%
aggregate(list(dat$interface),function(x){return(quantile(x,0.975))}))$x)

# Do not run
 copypaste::ctrl_c(res)

# Easy plot
plot(c(1,2,3),res$UB,,xlim=c(1,3),ylim=c(0,0.9),main="95% credibility
intervals",xlab='Interface',ylab='Error rate',col='white',xaxt='n')
axis(1, at=1:3, labels=c('Paper manual','Laptop manual','Mixed reality'))
points(1:3,res$Mean,lwd=10)
segments(1:3,res$LB,1:3,res$UB,lwd=5)
```