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Optimal Automatic Path Planning and Design for High Redundancy Robotic Systems

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Optimal Automatic Path Planning and Design for High Redundancy Robotic Systems

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In memory of my wonderful father

Abstract

Currently, streamlining of manufacturing processes rely on automation systems. Robotic solutions have been developed to enhance these automation systems. However, most production lines in industrial environments lack flexibility and adaptability, thus have limited capability to adapt to any generic task.

Importantly, the vast majority of the 2 million industrial robots in use today are still programmed online via the teach pendant approach. Two of the main reasons for this are the lack of absolute accuracy and the problems in generating automatic safe (collision free) tool trajectories for redundant systems, such as the common 6/7 axis industrial robots. A particular problem arises when these robots are integrated in workcells with extra degrees of freedom, such as external axis or positioners.

Another key challenge when developing industrial workcells is related with limitations of the shop floor design and organization of components.

The specification/design of high redundancy systems, including robot selection, tool and fixture design, is a multi-variable problem with strong influence in the final performance of the workcell.

This thesis focused on optimization techniques to deal with the optimal automatic path planning for high redundancy robot manipulators and the design of such systems. The approach included not only the geometrical constraints but also process and workcell constraints, such as speed, on-arm fixtures management (cables) and machine safety.

The algorithms developed and implemented in this thesis are generic enough to assure its applicability to several scenarios. A generic software tool to cope with the full extent of design and workcell execution is presented and validated using different workcell constraints and goals, but retaining the same methodological approach.

Keywords: Optimization. Path Planning. workcell Design. Industrial Environment.

Resumo

Atualmente, a otimização de processos de produção depende de sistemas automatizados. As soluções robóticas têm sido desenvolvidas no sentido de optimizar estes sistemas. Contudo, a grande generalidade das linhas de produção comummente encontradas em ambiente industrial carecem por falta de flexibilidade e adaptabilidade para serem aplicadas a qualquer tarefa genérica.

A grande maioria dos 2 milhões de robots industriais usados atualmente são ainda programados *online* usando a consola do controlador. Os principais motivos são a falta de precisão absoluta e os problemas de geração segura (sem colisão) de trajetórias para sistemas redundantes, como os robots industriais comuns de 7 ou mais eixos. Um problema que se adensa quando se integra estes robots em células com graus de liberdade extra, como eixos externos ou posicionadores.

Outro desafio crítico a ser ultrapassado em células industriais está relacionado com o projeto e organização de chão de fábrica. A especificação/projeto de sistemas de elevada redundância, incluindo escolha de robots, ferramenta ou componentes, é um problema multivariável com forte influência na performance final da célula.

A presente tese baseia-se em tecnologias de otimização para lidar com o planeamento de trajetórias ótimo para sistemas de elevada redundância e com o projeto dos mesmos. A abordagem proposta incluí, para além das imposições geométricas, condições da célula de trabalho, como velocidade, gestão de acondicionamento de componentes auxiliares (por exemplo, cabos), segurança da máquina, entre outros.

Os algoritmos desenvolvidos e implementados são genéricos o suficiente para assegurar a sua escalabilidade para diversos cenários. Desta forma, é formalizada uma ferramenta de software genérica capaz de satisfazer as necessidades de projeto e controlo da execução da célula, juntamente com a sua validação recorrendo a diferentes condições e objetivos de célula sob a utilização da mesma abordagem.

Keywords: Otimização. Planeamento de trajetória. Projeto de Célula. Ambiente Industrial.

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Throughout life it is expectable for everyone to challenge themselves to overcome difficulties and to reach higher levels of achievements. This process for me counted a reasonable number of supporters.

First, I would like to thank my supervisors Pedro Costa and António Paulo Moreira for giving me this opportunity and for their commitment over the past three years. Here, I need to thank Germano Veiga, for being so involved in the all project giving me unlimited research options and guidance. On a lighter remark, I also believe all the above acknowledge that this was an once in a lifetime opportunity to be a part of a brilliant project.

Then, a special mentioning to SARKKIS robotics and its collaborators. They opened their doors and gave me all the tools I required to succeed. I want to think the company has grown over the past years and I've grown with them. From the start that I've closely shared my weeks with three main characters from this action movie: Malaca (the old and patient one that glues the group), Daniel Marques and João Silva, the guys next door prone to give terrible headaches as well as optimal advices. Others have joined (and sometimes left) and for that deserve an acknowledge. The time that we share won't be forgotten. And last but not least José Oliveira for inviting me to two well deserved Christmas dinners but also for all the psychological effort towards my software development.

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In a more personal reflection, I have to mention my parents for their advices throughout my all life, for their sacrifices and all hard work that allows me to be here today, but mainly for showing me how to fight and overcome all obstacles.

Sometimes, life places unmovable obstacles in our journeys and dealing with them proves to be harder than expected. Nevertheless, I may be encouraged by parents and their relentless will in surpassing all these obstacles across all my existence and mainly during the last couple of years. Sometimes, life also isn't fair and takes away our best unconditional support. I know I won't hear some new advices and won't be able to share some of my biggest achievements with my forever remember father, however I also know that regardless of the form I will always be motivated to reach higher goals due to his endurance and his presence in my life.

My sister Adriana that hold me when I was a young baby and tried to protect me for as long as I can remember (despite hers almost giant-like height and weight), is the definition of wonder woman. She never fails in impress me despite all the high levels of admiration I already have for her. She inspires me to be better, and for that I need to be thankful.

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"Scientist investigate that which already is;
Engineers create that which has never been."

Albert Einstein

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List of Abbreviations

AEC	Architecture, Engineering and Construction
AGV	Automated Guided Vehicle
BIM	Building Information Modeling
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
COLLADA	COLLAborative Design Activity
DOF	Degree of Freedom
FEUP	Faculdade de Engenharia da Universidade do Porto
HMI	Human-Machine Interface
IFC	Industry Foundation Classes
IFR	International Federation of Robotics
IP	Internet Protocal
PLC	Programmable Logic Controller
PRM	Probabilistic Road Maps
RRT	Rapidly-exploring Random Tree
SDF	Simulation Description File
SME	Small and Medium-Sized Enterprise
TCP	Tool Center Point
TCP/IP	Transmission Control Protocol and Internet Protocol
UDP	User Datagram Protocol
URDF	Unified Robot Description File

Chapter 1

Introduction

The concept of smart manufacturing has prompted the start of a new industrial revolution based on automation solutions that can comply with the ever expanding industrial demands. This new trend, termed Industry 4.0, led to the development of a new system that enables innovative functionality through networking and access to the cyber world as discussed in Jazdi (2014).

The industry focus on automation enhancement, as defended by this new trend, is leading to a rapid development of the field of robotics. The inclusion of robotic components and solutions in industrial automation systems can increase the number of possible system solutions to a given problem, and, thus, increases industrial work flexibility. The development of intelligent robots means that robots can be defined as highly efficient operators and not only as stationary machines. Ultimately, via flexible robotic solutions, it is possible to program a robotic cell to cope with a wide range of challenges. Bahrin et al. (2016) mentioned that *robotics and automation technology is the basis of industrial manufacturing and an important driver for Industry 4.0.*, reinforcing the idea that uniting robotics and automation is core for streamlining industrial manufacturing.

Robotics is an expanding hot topic attracting the interest from both scientific and industrial communities. In fact, Tsuda (2018), the president of the International Federation of Robotics (IFR)[1], reinforced the importance of robotics following the adoption of robots across new geographies, industries and applications as shown in Figures 1.1 and 1.2

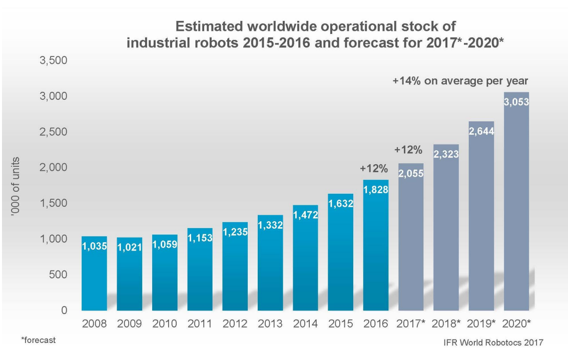


Figure 1.1: Forecast for World Wide working Industrial Robots

[1]https://ifr.org/

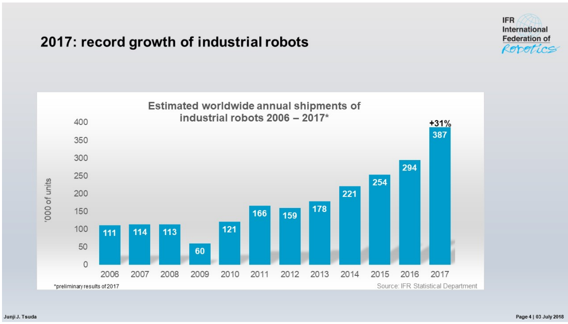


Figure 1.2: Sales Chart from 2006 to 2017

A more in-depth information, can be followed through the presentation "Revised Market Presentation CEO Roundtable 2018", presented in Automatica 2018[2].

A key contribution for the ever-growing interest in robotics pillars is its contribution for industrial financial growth. In their paper entitled “Robots at work”, Graetz and Michaels (2015) discussed the extraordinary influence that robots have on industry. For the first time, the economic impact of industrial robots has been clearly pointed out and recognition of their added value to industries is growing. This study is important due to the industrial focus shift currently experienced by industry. Today’s industrial core is mainly linked to the paradigm of Small and Medium-Enterprise (SME) and the productivity of these SME rely highly on automated processes, which were up until recently out of their reach owing to the high cost of historical robotic solutions.

Mikael et al. (2008) and Mocan et al. (2016) presented an overview on cost of robotic solutions, specifically the financial threshold to be overcome in order to provide feasible robotic solutions to industry. *Today’s business environment is dominated by change and uncertainty, and success within manufacturing is becoming more and more difficult to sustain*. Therefore, the concepts of flexibility and adaptability that currently robotic solutions are starting to offer allow one to consider robots as an efficiency catalyst and a well applied resource in any given production line.

Another relevant topic trending within the industrial community is related to project scalability. Under this new concept of Industry 4.0, having a modular component solution that can easily be reconfigurable to multiple production and manufacturing lines is crucial to ensure industrial efficiency. In line with this view, Weyer et al. (2015) defended that to ensure the Industry 4.0 success, proprietary approaches should be replaced by standard modular solutions. Despite all scientific and industrial support towards the development, validation and implementation of robots in the factories of tomorrow, there are still major obstacles to be overcome when considering robotic programming, as described in by Pan et al. (2012).

To date, most industrial robotic solutions are still programmed on-line by human operators using the teach pendant approach. The operator empirical experience of previous tasks is still the default solution for many industrial corporations. The reasons behind this dead-lock are two-fold. First, the lack of absolute accuracy along a programmed operation. Second, the problems associated with automatic generating safe (collision free) tool trajectories for high redundancy robotic

[2] https://ifr.org/ifr-press-releases/news/industrial-robot-sales-increase-worldwide-by-29-percent

systems, such as, the traditional industrial robotic manipulator of 7 or more axis. Another difficulty limiting wider adherence to robotic solutions in the industrial environment, linked with the second problem described here, arises as a consequence of the need to insert extra degrees of freedom, such as, external axis, jigs or positioners, to comply with industrial flexibility requirements.

The need for high redundancy systems bring up other critical issues in robotics. The specification/design of such systems is a complex problem with strong influence in the overall efficiency and effectiveness of a given implemented solution. This is a multi-variable problem that includes component and fixtures design, and subsequent placement, that enables the optimal completion of industrial operations. The lack of flexible solutions for vertical integration of all robotic processes is another obstacle due to the complexity of the technical design and the control operations for optimization of the cell work required to reach the desired goals. This thesis aims to develop an optimal flexible solution to overcome the robotic limitations outlined above.

1.1 Current Robotic Optimization State

Optimization algorithms have been applied over the years to achieve an efficient catalyst for all existent areas of knowledge. However, in robotics this as been an overlooked consideration as most solutions are focus in providing a good standalone implementation for a contained problem.

Industry 4.0 and today industries' accept robot as an efficiency enhancement and force a paradigm shift towards automatic optimal solutions based on robots. The optimization of configurations, efforts and workcell design is a new problem that arises in importance due to flexibility challenges in industry. Nevertheless, despite its tremendous potential, there are still important voids that must be addressed as there is no complete solution in that regard.

1.2 Thesis Statement

The robotic field's expansion fosters the development of highly autonomous and efficient methodologies to address: (1) the prominent research and development problems and (2) the application of research solutions to industrial environments. Thus, throughout this thesis work, I will aim to prove that the development of complete yet flexible and modular motion planners, which are able to consider scheduling of tasks and surrounding environment, allied to novel methodologies, capable of defining the correct workcell for a given operation in robotic industrial applications, is feasible and essential to achieve industrial requirements and empowering production goals.

1.3 Thesis Goal

Currently, there is a need to develop a robust and flexible engineering solution focused on motion planning for high redundancy robotic systems. Equally, there is a need to develop a revolutionary novel algorithm to aid robotic workcell design, given that currently there is still no viable solution in this field and the design optimization is clearly a solution with an interesting added value. These contributions are of great value for both robotic and industrial areas.

Thus, the goals for this thesis are:

1. Develop a simulation tool transversal to any high redundancy robotic system and compatible with commercial software to ease the information flow from CAM software to on-site industrial production lines.
2. Define a robust planning solution, generic enough to be applied to multiple robotic system, regardless of brands and complexity.
3. Create an optimal and innovative framework for robotic workcell aided design.
4. Formalize a modular solution package to integrate both optimization methodologies - a great need on today's industry.

1.4 Thesis Timeline

Throughout the months that led to the development of the robotics methodology presented here, there were a set of stages to be achieved. These stages are:

1. Identify the current state of technology in optimal automatic path planning and workcell design.
2. Identify the key faults on automation system and its possible corrections.
3. Define the set of key parameters, considering geometrical constraints but also processes and workcell constraints, such as speed, on-arm fixtures management (cables), machine safety, among others.
4. Development of a simulation framework model to validate this thesis' algorithms.
5. Development of an optimal automatic path planner.
6. Development of an optimal workcell setup software.
7. Development of an optimal specification/design methodology.
8. Development of an integrated solution.
9. Validation of these algorithms in industrial environment.

These can be segmented into three main stages. First, deep scientific research to correctly identify faults and useful contributions for a more successfully development of the proposed solution. Second, the development of the solution itself and a generic test framework to critically assess any iteration along the process. And finally, the validation of the developed solution using real scenarios in both simulated and industrial environments.

1.5 Thesis Company - SARKKIS Robotics

SARKKIS Robotics is a software company specialized in robotic cutting and welding (SARKKIS (2019)).

Originally a start-up from the University of Coimbra, SARKKIS has been created in 2011. Following its creation, SARKKIS focused on developing steel industry solutions namely for cutting and welding while creating some automation-aiding devices (such as PEMtank, a pressure controller device).

SARKKIS Robotics has developed multiple software to generate automated vector for the welding and cutting operations. These software are key to ensure operation quality, defining robots' final position, trajectory velocities and operation parameters.

The company has participated already in multiple scientific projects under some grant agreements. Some examples include CLARiSSA[3], CoopWeld[4] and ScalABLE 4.0[5]. CLARiSSA and CoopWeld resulted in state-of-the-art machinery for welding, while ScalABLE 4.0 is an on-going project following the fundamentals of Industry 4.0.

At last, this company also has multiple international projects implemented and validated. Figures 1.3 and 1.4 show some of these workcells.

Figure 1.3: Examples of Cutting Installation by SARKKIS

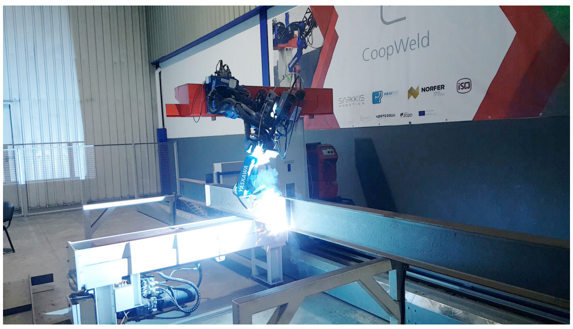


Figure 1.4: Examples of Welding Installation by SARKKIS

[3] http://www.sarkkis.com/mechatronics/rd/smerobotics-clarissa/
[4] https://www.coopweld.com/
[5] https://www.scalable40.eu/

1.6 Thesis Contribution

The work presented here builds onto currently available optimization techniques while addressing crucial pitfalls of today's robotic systems. Currently, these systems lack in flexibility to be applied to multiple industrial contexts. The surrounding environment and the components must be bound as most software solutions are custom design for a single workcell or work type. Furthermore, to date, most industrial sites require an experience operator to handle with these machines. Therefore, constraints on time consumption for robotic programming or adjustment to mechanical faults is overlooked.

The proposed methodology includes optimal automatic path planning and design for high redundancy robotic systems. This approach will not only include geometrical and user constraints, but also considers workcell constraints, such as speed or dynamic stability, auxiliary components disposed along the cell, such as on-arm fixtures management (cables, welding feeder, sensors) or fixed stands, machine safety, among others. The development and implementation of this methodology obeys to the fundamentals of Industry 4.0 and the concepts of modularity. Each level of decision throughout the processes of design and control is composed by a flexible solution that uses similar parameter definition to comply with different scenarios and demands.

Furthermore, the proposed approach was developed in coordination with a highly specialized robotic development industry. This allowed for refining of the main optimization sections and validation of them in real industrial scenarios.

The developed solution can be used in scientific projects to solve high level design problems, such as prototype development. However, it is mainly directed towards the industrial community, which can use this work to safely and accurately control or design their robotic solutions, under the harsh constraints commonly found in industrial environment.

The usage of the simulator framework developed allows the end user to both preview the behaviour of a complex robotic system and to use the added value of the digital twin methodology to keep up with the real industrial system on real time. Furthermore, the modifications inserted on the SARKKIS CAM software allowed to improve on the previous commercial solutions by inserting intelligence on tool path vectors generation.

Robotic optimization is a hot trend in today's industrial field. Nevertheless this is mainly focusing mechanical constraints while the software is overlooked. The study on optimization methodologies stemming from this thesis work provides a better insight on advantageous optimization techniques applied to robotic systems. Then, developing a genetic-based algorithm for path planning and design proved to be a paradigm shift towards the right direction in the robotics area. The time consumption is clearly lower than current methodologies used without damaging the final outcome.

Finally, the real winners from this thesis work have to be the industrial facilities where this work has been used or is currently being installed. Despite all pitfalls in robotics and automation, this thesis work continuously proves to be an optimal fix in workcell control and planning, and a great assistant when considering the implementation of current and future shop floors. Therefore, to date, it is possible to confirm that the proposed methodology has a high added value in logistics planning and robotic operation management, being ultimately a solution that both industrial and scientific communities should be driven to implement.

1.7 Document Structure

The following thesis is divided into seven chapters. Chapter 2 intends to provide an overview on the current state of the robotic field and the associated obstacles to overcome. Then, Chapter 3 explores in detail some of the most useful mathematical conditions and relations that are critical for the solution implementation. Once dealt with the robotic familiarization, Chapter 4 presents an overview on the software framework base used in this thesis. Chapter 5 provides an insight on the layer that hold this thesis project, followed by the specification of each optimization components for each step of the process. At last, Chapter 6 demonstrates validation use cases, presenting the final results upon applying the proposed solution, ending in Chapter 7 that critically assesses this work and and discusses futures perspectives of it.

Part I

Theoretical Background

Chapter 2

Robotic Background

The automation field is rapidly exploding in terms of solutions range and impact seen in industrial environments. Throughout this chapter, an overview will be provided on present and future contributions from automated system, in particular robotic solutions.

Automation solutions are seen as the most viable tools to overall process improvement. The demand for complex and difficult tasks across all production areas prompted the usage of these solutions, however, there is a high degree of inertia when it comes to the adoption of solution updates and industrial developments, since that industrial corporations tend to be slow in adopting these technologies which is an important hurdle to overcome. Nevertheless, past studies pointed out the high benefits regarding cost reduction and productive increase when automation solutions were implemented in the industrial setting. Kutay (1989) demonstrated *the inadequacy of current economic analysis techniques to assess the benefits of automation technology*, suggesting that automation technology should lead both academic and industrial development.

Currently, and despite some opposition, automation thrives as a key catalyst for process efficiency improvement across all areas. Shariatzadeh et al. (2016) explored a new beneficial approach for distribution systems based on automation systems and control. Li et al. (2017) proposed a cooperation between automation and medicine that can prompt a personalized health treatment. Another case of this cooperation is the increase of quality of laboratory using automated guidance equipment as portrait by Zaninotto and Plebani (2010). Furthermore, automation system manage to improve work environment conditions. An in-depth study was conducted by Kaber and Endsley (2004) exploring the effects of automation systems and its interaction with human operators upon a dynamic task control.

These developments led to a new industrial revolution that is precisely based on automation and its usage: the Industry 4.0. This new industrial era intends to develop well rounded solutions to cope with the most complex challenges found in industrial facilities and, here, robotic solutions can be consider as industrial efficiency enhancement systems. Robotic systems provide enough programmable flexibility to be considered reconfigurable automation technologies. Therefore, they are optimal solutions within this new concept of Industry 4.0. The main challenge is to bridge the existent industrial demands and current robotic framework.

2.1 Robotic Evolution

The ever-growing development of the robotics field is associated with the scientific and technological development of both software and hardware. The need for efficient automation methods has prompted the rapid development in the Robotics' field.

Industrial corporation first usage of autonomous structures dates back to 1938. At the time, the English magazine Meccano (1938) published a crane-like structure developed to automatically assembly small constructions. However the industrial robot concept is only acknowledge two decades later. George Devol and Joseph Engelberger developed the first official industrial robot, the Unimate. Robotics.org (2018) presented an online paper tribute to Joseph Engelberger identifying this robot. However, as expected, this first robot had some important issues to address. The prototype weighed two tons, was built around hydraulic actuators and its precision was reduced. Moreover it was not a flexible robot as it would only perform the pre-inserted source code. Nevertheless this was the starting point for the robotic development which through the years focused on the condensation, simplification and the increasing insertion of intelligence of its construction.

Throughout the last decades we've witnessed the use of fixed robotic manipulators in a wide range of applications due to their efficient behavior in harsh environment and high precision demanding operations such as onshore oil and gas industry or naval industries, among others as defended by Shukla and Karki (2016) and by Garnier et al. (2018). Multiple other harsh and complex operations have been assigned to a capable robot. Examples of these application have been presented by Khurshid and Bing-Rong (2004) focusing the military possibilities and by Chen et al. (2009) regarding the assembly operation. Nowadays, it is even possible to consider fully autonomous warehouses as defend by Amazon or presented by Guizzo (2008).

Another key application for robotic systems using manipulator arms is also related to transportation. Recently, Madsen et al. (2015) evaluated the use of autonomous manipulation technology in a real world industrial manufacturing environment. The benefits of using robotic solutions in the industrial environment range from increased efficiency to minimized costs and reduced operating times. However, the same study points several aspects requiring further research before the technology can be made available to the wide industrial world. These included: robustness, safety, standardization, and robot and workstation re-configurability.

Despite the tremendous utility that robotic solutions add to the industrial world, the ones in use in the industry lack flexibility to autonomously react to changes. Most of those solutions were implemented without using a modular approach. Consequently, a minor change in the required task could lead to a complete restructuring of the source code that controls that robot. A possible solution to overcome some of the current limitations of available robots rely on the use of modular based software.

The following sections will build on the hardware development of today's robotics (section 2.2), the robotic development regarding system control and planning (section 2.3) and the optimization procedures commonly found in robotic systems (section 2.4).

2.2 Robotic Hardware Background

The exponential evolution from the first robot till today and the growth of the scientific and research community led to a large improvement and perfecting of the robot structure. The next subsections will provide a brief overview on the main elements of a robotic system. A special focus will be given to industrial scenarios.

2.2.1 Robot Manipulators

Industrial robot manipulators can be classified and distinguished by their constructive geometry, resulting in two major manipulator types: parallel and serial.

The serial architecture is defined as a series of links (rigid bodies) connected by a set of motor actuated joints ranging from robot's base to the robot tool center point (TCP, typically the actuator to handle objects or perform tasks). The parallel architecture consists of a robot equipped with a tool with multiple one order independent kinematic chains connected to a fixed base. Following this architecture the robot is controlled by a set of actuators in equal number to its DOF. The main advantage is related to the high speed, acceleration and precision while having a reduced inertia when compared to the serial architecture. Examples of this kind of robots are presented by Bonec (2015), Nabat et al. (2005), Mecademic (2014) and Bristol (2011).

Despite the advantages associated to these kind of robots, the serial architecture has an inferior cost while its robustness is well fitted for industrial purposes. The most standard configurations for this architecture have been discussed by Spong et al. and are presented next in Figures 2.1, 2.2, 2.3, 2.4 and 2.5.

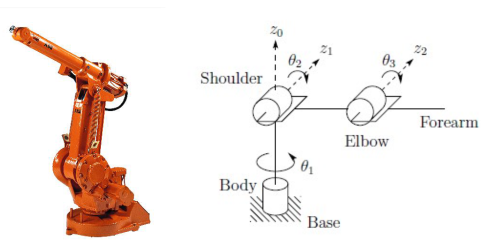


Figure 2.1: Anthropomorphic Robot (ABB IRB1400) Spong et al. (2006)

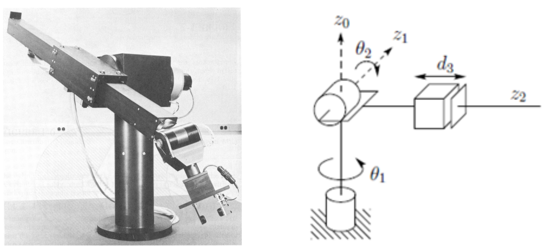


Figure 2.2: Spherical Robot (The Stanford Arm) Spong et al. (2006)

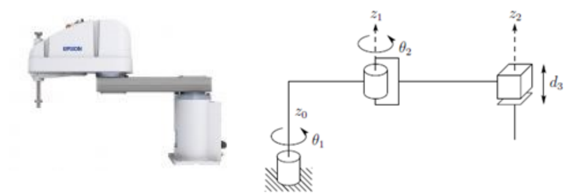


Figure 2.3: SCARA Robot (Epson G20) Spong et al. (2006); EPSON (2015)

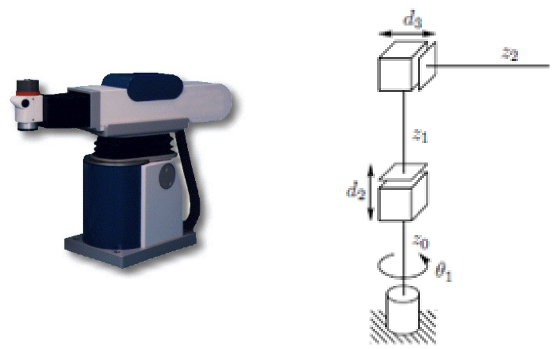


Figure 2.4: Cylindric Robot (Seiko RT3300) Spong et al. (2006)

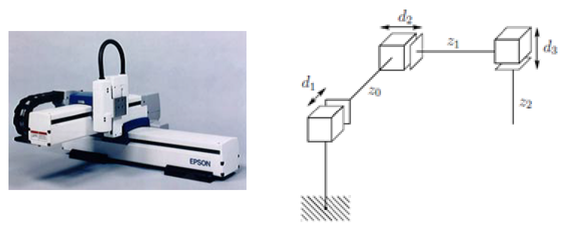


Figure 2.5: Cartesian Robot (Epson Cartesian Robot) Spong et al. (2006)

Most industrial robotic manipulators follow one of the previously presented configuration (typically an anthropomorphic configuration), however they are extended using a wrist element (explored by Romiti et al. (1994)) providing three extra DOF, thus, reaching the 6DOF.

A new variant is emerging using 7DOF robots instead of the typical 6DOF. Conceptually they follow the serial architecture, gaining additional freedom to avoid some robotic pitfalls that occur when using 6DOF robots as discussed in Kuhlemann et al. (2016). The number of connecting motor joints is scalable with the robot requirements for movement freedom and dexterity. It is possible to find prototype robots using over 10DOF systems, however, the control and the modeling of high DOF robotic hardware increases in complexity with the number of joints.

Recently the concept of human robot collaboration prompted the development of safe and user-friendly robotic hardware. Maurtua et al. (2017) defines this collaboration as *a key factor for the development of factories of the future, a space in which humans and robots can work and carry out tasks together*. In another work, Awais and Henrich (2010) defend that combining *the intelligent and situation dependent decision making capabilities of a human with the accuracy and power of a robot, performance of many tasks can be improved*.

These robots were designed to be light and easily adaptable to share work sites and workloads with other robots and humans in fully safe manner. Thus, the unlimited possibilities they present has grown a lot of interest by the robotic community.

2.2.2 External Axis & Positioners

Robotic systems have been developed towards the increase of flexibility. Therefore, multiple complementary solutions to provide extra degrees of freedom arise in importance. These can be inserted within a robotic work chain or may be used as an auxiliary tool to provide external motion or to re-position stationary parts.

The first group manages to improve on the common robot flexibility adding motion range. Multiple studies have discussed this approach and present optimistic results based on its usage. Deng et al. (2012) presented one of several applications currently using these kind of devices.

Industrial corporations accepted this new paradigm and, currently, it is possible to see the use of these systems in welding, cutting, painting, among others industrial operations, based on the usage of track and/or rigs. These systems are now produced in a standardized way and their development required some customizable software and, thus, they were not entirely developed considering a flexible and generic approach. It is also important to note the complexity of these stations. As an example, in Figure 2.6, we have three different movements to cope and control: (1) the translation of the material to be cut place on a conveyor, (2) the rotation of the structure holding the robotic manipulator and (3) the manipulator itself. Still, this is now a problem with a unified codification and its development assures quality and efficiency to any production line.

Figure 2.6: Multi DOF robotic cell

The other already mentioned group is based on re-position supportive elements that allow to replace objects of interest. These can be anything from beams to smaller or infinitesimal components commonly found in the pharmaceutical, electrical communications or technological areas.

Among others, in industrial facilities the tendency is guided towards the usage of positioners, tables, turns and conveyors. These present themselves as a well rounded solution for a wide range of applications for both manual or automatic (or even robotic) systems.

The use of one of these components can accelerate production and improve overall process quality. RobotWorx (2019) (a well known robotic company) provided a summary on the importance of their usage and the utility they can add.

Despite of the increased flexibility these sub-systems provide to robotic cells, there is untimely an acknowledge solution for maximization of motion range of a given robot. Automated guided vehicles (AGVs) tackle the obstacle of stationary robotic system and present an autonomous solution that can thrive in well specified environment. Nevertheless, they imply several logistic modifications so that they can function accordingly to plan.

Regardless of the system, these solutions build on top of four main principals: flexibility, accuracy, safety and productivity. Robotic systems can be upgraded using these components and their usage has become usual in most workcells.

2.2.3 End-Effectors

A crucial component in every workcell is related to a robot end-effector. These are the tools able to complete the underline task. Boubekri and Chakraborty (2002) well described the importance of these tools, defending that a *robot is able to perform a task adequately only when it is assigned proper tooling and adequate methods of grasping and handling work pieces*.

There are several possibilities and the correct choice of tool to use relies on the application purpose. Nevertheless it is possible to divide them by groups: grasping tools, actuation tools and sensors.

A large part of common robots that intend to manipulate, transport or match components (through pick and place or bin picking operations), typically find an attached grasping tool to their last link. These tools can be programmable controlled and provided multiple opening patterns (an advance example is present in Figure 2.7) or logical controlled by a pneumatic valve that actuates through a complete opening or closure of claws.

Figure 2.7: Robotiq Grippers

Some other revolutionary solutions have emerged lately by using different techniques. For example, the request for more flexible and effective solutions to grasp uncommon objects prompted the development of grasping devices able to adapt to the object shape and consistence (an example of this are the magnetic grippers or the VERSABALL gripper, found in Figure 2.8).

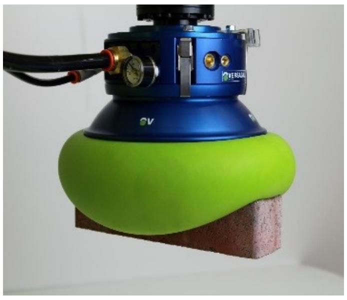


Figure 2.8: VERSABALL Gripper

Despite the flexibility these tools provide, to comply with industrial requirements, there is the need to adapt the robot structure to allow for higher complexity operations such as welding, cutting, painting, screwing, among others. Essentially the robots assume themselves as machine operators and attached to their structure is a task completion tool (welding or cutting torches, screw drivers and others, as portrayed in Figure 2.9).

Figure 2.9: Application Robots (welding, painting)

At last, sensorization of surrounding environment is key to ensure efficient task completion. Despite all efforts across the installation part of a robotic cell, it is not possible to ensure optimal placement of components. Furthermore, the repetitive usage of the components will most likely result in component wear and consequently to modification of its function and/or placing.

In this regard, recognition aiding equipment has been developed to properly identify and correct mismatches between theoretical scenarios and shop floor real installations. These are mainly visual detection devices (such as cameras) or reflection response system (lasers). Cameras typically are applied in workcells where there is a requirement to visual inspect and/or detect components, sub-parts or eventual faults. Lasers, either dot-lasers for higher accuracy or line-lasers for higher reach, are a local solution capable to correct mismatch with extreme high accuracy.

Other equipment also arise in importance in modern robotics. To date, it is possible to list a wide range of sensors with multiple purposes, from identifying materials to evaluating production performance.

2.3 Robotic Control Background

Throughout the technological development and the robotics expansion, there have been multiple investigations regarding motion planning and task management. Motion planning is a key area of robotics. It comprises path planning algorithms, configuration space discretization strategies and related constraints. On the other hand, task management is an area with increased relevance as the optimal scheduling and step definition of a given task is desired to reduce both costs and time expended with such task.

A review on a large set of solutions for motion planning has already be presented by LaValle (2006). There are two main approaches for motion planning: reactive (Overgaard (1996); Naruse and Kakazu (1995); Belkhouche (2009)) and non-reactive or deliberative path planners. Most robotic solutions are based on non-reactive path planners. These have the ability to define a path between two points as long as there is one available (they are complete). Within this group, there is a further division: sampling-based or discrete optimal planners.

Sampling-based planners are the most common for robotic applications. This concept relies on avoiding obstacles zones iteratively throughout time (e.g. Probabilistic Roadmaps or Rapidly-exploring Random Tree, Karaman and Frazzoli (2011); Jaillet et al. (2010); Moll and Kavraki (2006); Yoshida et al. (2008); Aoude et al. (2013)). Discrete optimal planning focuses on creating complete and optimal paths. These require a pre-processing of all possible configurations that the robotic solution may reach, ensuring a faster execution time, despite a large setup time. Examples of these planners are the A* and its variants, found in multiple scientific contributions (Zhang and Zhao (2014); Cui et al. (2012); Trovato and Dorst (2002); Blackmore and Williams (2006)).

It should be noticed that despite the relevance of the topic for the research community, the use of automatic path planning in industrial scenarios is almost null. This is mainly due to memory management problems and delay in obtaining results. Path planners to be computational viable require space discretization. Hwang and Ahuja (1992) explained its key steps and pointed hypotheses concerning the robot's surrounding environment discretization. Once detected the surrounding environment of the robot, there is the need to define a configuration space for the same robot. Thus, initially, we have to consider a way to transform the 3D space into a discrete space of configurations. Another aspect to consider is the kinematics associated to the selected robot. This aspect allows one to associate the current state of the robot with a Cartesian pose.

Although the already presented studies marked the beginning of autonomous and motion controlled manipulator arms, a crucial evolution was the integration of obstacles avoidance algorithms proposed by Yao et al. (2008).

The comparison between both variants presented above has generated a high amount of disagreement. However, it is clear that there are advantages in both approaches. While probabilistic methods may have a higher execution time to define a path, they can achieve high precision of the final desired pose and can avoid memory management problems. On the other hand, complete planners define the correct path to achieve such pose. A simple comparison table can be found next in Tables 2.1 and 2.2.

Algorithm	**Time Effort**	**Memory Issues**
Probabilistic Algorithms		
PRM	Low	No
RRT	Low	No
Complete Algorithms		
Djisktra	Very High	Yes
A*	High	Yes
D*	Medium	Yes

Table 2.1: Path planners Comparison: 1/2

Algorithm	**Precision of Final Pose**	**Optimal / Complete**	**Collision Avoidance**
Probabilistic Algorithms			
PRM	Exact Pose	No / Yes	Yes – Demands Recalculation
RRT	Exact Pose	No / Yes	Yes – Demands Recalculation
Complete Algorithms			
Djisktra	Cell Dependent	No / Yes	Yes
A*	Cell Dependent	Yes / Yes	Yes
D*	Cell Dependent	Yes / Yes	Yes

Table 2.2: Path planners Comparison: 2/2

When designing a robotic system, it is also necessary to consider a control tier that regulates the system movement and minimizes the errors throughout the operation. This is one coupled issued to robotics.

Many approaches have been suggested. Murray and Sastry (1993) proposed one basic method for steering systems with nonholonomic constraints. Despite following a simpler problem, this method has proven to be limited when it comes to the difficult control of motion. More recently, another example is presented by Son (2002) that suggested a learning algorithm that together with a fuzzy optimal process was able to facilitate pick and place approaches. Moreover, Son (2011) also demonstrated that it was possible to avoid jamming by using measured force and moment information.

The dynamic section of this process is also relevant. LaValle and Kuffner Jr. (2001) designed a kinodynamic planner *to determine control inputs to drive a robot from an initial configuration and velocity to a goal configuration and velocity while obeying physically based dynamical models and avoiding obstacles in the robot's environment* focused on multi-DOF workcells.

All these constraints can be regarded as a single multi-layer problem, and the need for a packaged solution arises.

2.4 Robotic Optimization Background

Optimization algorithms have been applied over the years to achieve an efficient catalyst for all existent areas of knowledge.

Recently optimization approaches were deemed necessary to the scheduling of processes and technology-driven solutions proved to be useful to overcome some of difficulties related to process time. Technology made it possible to achieve optimal results in a viable time frame Mathew et al. (2014).

For the robotic field, the main challenge throughout the years has been to control the robot unit perfectly to comply with highly demanding requirements and low error acceptance. The control of the dynamics associated to the robotic cell is therefore an almost solved problem.

However the optimization of configurations, efforts and workcell design is a new problem that arises due to increasing demand for high robot flexibility and modular challenges that are common in today's industrial environment.

The development of intelligent robots leads to the ability of them becoming a highly efficient operator, able to adapt to a wide range of problems. To date many approaches have been considered to address the industrial challenges while delivering on the most suitable solutions for autonomous and robust robots. In that regard, robots present themselves as a key component for the optimization of manufacturing processes. Some studies have been conducted to validate precisely the efficiency of robotic solutions usage and the need to define a selection method for system configuration Komašilovs and Stalidzans (2012); Komasilovs (2013).

Furthermore, the concept of optimization is highly associated to robotic operations. Robots help to reduce the cycle time of assembly lines and enhance quality assurance compared with handmade production. Therefore, efforts have been made towards the ability of intelligently insert robotic system constraints that validate its efficiency and optimize the execution of the proposed task. Despite lacking a formal approach, these optimization techniques have surge within the scientific community providing solutions for workcell configuration and trajectory planning Čejka and Černohorský (2016); Mombaur et al. (2014).

In that regard there are some studies pointing towards a possible solution. The array of possible implementation range from task specification constraints to risk analysis. All these provide viable inputs to a decision making optimization methodology to comply with pre-established system requirements Trianni and López-Ibánez (2015); Neacşa et al. (2013); Feng et al. (2010).

There is still a prominent problem in robotic systems regarding task management, which involves the integration of the motion planning in the workcell context, including technological process limitations, communication with external devices, automatic workcell calibration among others. Currently, there is no optimal tool to create an action sequence to complete a given task (currently handled by human experience). However, some studies point to the usage of optimization functions to attend this problem (Bennewitz et al. (2001); Alatartsev et al. (2015)). The integration of automatic workcell calibration tasks with the motion planning is crucial for the use of planned tasks in the real environment and this topic have been only briefly approached (RoboDK (2015)).

Another key topic in robotics is related to the workcell design, that comprises, among others, robot selection and fixture design. Cheng mentioned the simulation tool's advantages in order to develop a robotic workcell Cheng (2000). Furthermore, there have been authors claiming to find powerful enough methodologies to handle machining and welding challenges Andrisano et al. (2011); Hauer et al. (2009).

Still, despite its importance, existent robotic systems are focused on solving separate necessities while there is no optimal tool to properly design a generic robotic workcell. The nearest solution to an optimal design methodology was presented by Kamoun et. al, when they presented an approach concerning the display of equipment over a given area Kamoun et al. (1999). However, the approach only considered previously selected equipment and did not include the optimal selection of such equipment.

Despite its tremendous potential, optimization of robotic postures, configuration, kinematic assembly and other key stages in workcell control and design have been overlooked over the years.

2.5 Industrial Robotic History

The demand for robotic driven solution has exponentially grow over the years. The IFR studies point to an increase of the number of working robots in industrial shop floor. On appendix **??** graphs can be found to back these statement. Robotic solutions can be consider to be industrial efficiency enhancement systems.

Over the past decades, efforts have been made towards flexible robotic solutions. Inserting intelligence in robotic systems leads to the concept of multi tasking robot. This is key in today's industrial demands. Robots need to be considered a flexible and modular solution able to be applied in any production stage, facing dynamic constraints imposed by the surrounding environment as proposed by Eustace et al. (1993); Shi and Menassa (2010).

In the current state of technology, several applications have been designed to integrate and use automation and robotic solutions with the remaining industrial components and even with the human operator. Currently, it is common to identify the robot as an highly efficient operator that can cope with both industrial demands and human interaction as defended by Schou et al. (2018).

The following subsections will describe the advances in industrial robotic applications (section 2.5.1) and in new robotic solutions currently deployed in a wide range of shop floors (section 2.5.2).

2.5.1 Industrial Robotic Applications

The introduction of robots in multiple areas of industry is already a reality. Edwards (1984) argued that the robots appear to be able to be applied in a wide variety of settings, performing a wide range of functions. Currently it is possible to identify robots in highly automated environments such as the automotive industry (Grohmann (1996)) or even in the food industry (Ishii (1997)).

Another important industrial development regarding robots is their ability to collaborate with human operators. An official International Standard ISO/TS 15066:2016 (ISO (2016)) has been defined in order to accommodate this ever growing interest of having both robotic systems and human operators working towards the completion of a task.

Nevertheless, a big contribution for the rapid development of efficient robotic solution is the metal industry. This industry demands and the integration of robots in their shop floor led to a wide range of flexible solution that can be extended to other scientific and industrial domains.

Currently, the steel fabrication industry is also demanding the automation of several inherent production processes, as a way to shorten the project's life cycles and reduce the related costs. Several applications can be found actively working in industrial shop floors. These solutions vary from automatic robotic cells for welding and surface treatment and automatic handling as pointed by JIvkov (2011). Such advanced robotic systems become effective as a standalone partner in construction.

Karabegovic et al. (2012); Karabegović et al. (2013) even state that *automation and modernization of a manufacturing process in any industrial branch is impossible without industrial robot application*. Some examples of these application can be found in welding, cutting, pick and place and other operations commonly find in metal industry (Chu et al. (2013); Jung et al. (2013)).

2.5.2 Industry 4.0 Robotic Integration

Recently, a new industrial trend is emerging. This new revolution identified as Industry 4.0 is represented by the concept of cyber-physical systems and Internet of Things (IoT). These premises intend to create a new paradigm shift in industries inserting smart systems and ultimately creating smart industries.

Here, it is possible to advertise robots as facilitators for this technological upgrade. Wan et al. (2015) defines this new concept as the enabler for technology where it is *possible to closely integrate the physical world with virtual world*.

The collaboration between robots and human operators is also key for the development of this trend. Benotsmane et al. (2018); Vysocky and Novak (2016) proposed that following this innovative strategy the objective is to build up an environment for safety collaboration between humans and robots, where both can thrive.

Nowadays, manufacturing and production processes are starting to be defined as a set of skills that both human operators and robots can address. In that regard, it is important the introduction of Industry 4.0 in robotic systems. Currently, it is possible to design a system where the robot is flexible enough to understand the industry requirements following a communication protocol and execute accordingly.

Among others examples, Han (2018) reviewed one of the applications of this methodology where the robotic system is able to perform a task and report on it closing the information loop of a given operation.

There are multiple other examples following this trend. Robots can be seen as monitoring devices as presented by Gonzalez et al. (2018) or transportation/operation helper using modified AGVs (Neradilova and Fedorko (2017); Theunissen et al. (2019)). Industry 4.0 appears to be the perfect catalyst for robotic development and insertion of these robotic system in industry.

2.6 Chapter Summary

The development since the Unimate is exponential. Today, robots can be considered highly efficient operators capable of supporting a wide range of applications across all scientific and industrial areas.

However there are some paradigms regarding robotic usage that should be addressed. Sauppé and Mutlu (2015) carried a study to address the social impact of using robot solutions under industrial conditions. Despite the challenges ahead, robotic solutions present themselves as key for streamlining manufacturing future.

As defended by Pedersen et al. (2016), the current shift in industrial production, requires automation that can effortlessly be reconfigured or re-purposed. However, current robotic solutions still lack flexibility to be applied to multiple industrial scenarios.

Robotic systems are becoming highly efficient operators. Thus, its optimal design and motion planning are key steps to ensure industrial productivity and success.

Chapter 3

Robotics Kinematics and Dynamics

Throughout this chapter, the mathematical relations associated to robot motion will be explored. In Section 3.1, it will be explored the concept of kinematics, while in Section 3.2 it will be presented the main dynamic fundamentals and its mathematical correlations.

3.1 Kinematics

Kinematics is the concept of describing physical motion of bodies based on mechanical joints position. Therefore, as defended by McCarthy (1990), robot kinematics is essentially a geometrical exercise to determine the influence of multi-DOF chains, associated to robotic systems, in the global robot motion.

Here, we can have both direct and inverse kinematics. The first is the process of determining the final position of a robotic system based on its current joints' state. In order to do so, the first step is to define a coordinate system associated to each robot element (referenced as link, from this point forward) that connects two motored controlled joints. This coordinate system is able to describe the relation between the several robot links following a set of translations and rotations. Several studies were already conducted in this regard. Some examples are: Mouly and Merlet; Oetomo et al.; Merlet (1993). Thus, it is possible to establish a linear transformation matrix between consecutive referential. This matrix can be defined as:

$$\mathbf{T_y^x} = \begin{bmatrix} \mathbf{R_y^x} & \mathbf{\tilde{P}_y^x} \\ 0 & 1 \end{bmatrix} \tag{3.1}$$

R_y^x is the rotation matrix that describes the rotation between the x and y referential, while $\vec{P}_y^x$ is the translation vector between the same referential. Furthermore, and as a consequence of this definition, the final transformation from base to end-point can the express as the cycle product of multiple matrices:

$$\mathbf{T_N^0} = \mathbf{T_1^0} * \mathbf{T_2^1} * \mathbf{T_3^2} * \ldots * \mathbf{T_N^{N-1}} \tag{3.2}$$

Denavit and Hartenberg explored this concept of linear transformation matrix and proposed a method (DH) to clearly identify each relevant component for this matrix. Therefore, the homogeneous transformation presented before may be defined by the DH parameters as presented next:

- a_i - distance between the *i-1* axis and the i referential origin, o_i;
- α_i - angle between *i-1* and *i* axis in the normal plane to x_i;
- d_i - distance between *i-1* referential origin, o_{i-1} and x_i axis;
- θ_i - angle between x_{i-1} and x_i axis in the normal plane to z_{i-1}.

Based on these values, it is, thus, possible to determine the homogeneous transformation matrix of all referential, generically defined as:

$$\begin{bmatrix} cos(\theta_i) & -sin(\theta_i)*cos(\alpha_i) & sin(\theta_i)*cos(\alpha_i) & a_i*cos(\theta_i) \\ sin(\theta_i) & cos(\theta_i)*cos(\alpha_i) & -cos(\theta_i)*cos(\alpha_i) & a_i*sin(\theta_i) \\ 0 & sin(\alpha_i) & cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

The inverse kinematic allows to do the reverse exercise. Therefore, it allows to translate a cartesian space transformation into a set of joints' state values. Despite the controller evolution, most of robots are controlled by joint space instruction and, as such, applying the inverse kinematic method in mandatory for robotic motion control.

Here, one of major problems in robotics arises. While it is possible to apply the inverse kinematic to common 6-DOF robots with a spherical wrist using an analytically approach, the same can't be applied to higher complexity robots or even with robots with wrist offsets. Both cases will be presented next.

3.1.1 6-DOF Robots With Spherical Wrist

The most common industrial manipulators are 6-DOF robots. As indicated by the number of DOF, these robots are equipped with six motor-controlled joints. Therefore this would be a six variable problem. A cartesian space transformation may also be defined as a six (using euler angles) or seven (using quaternions) constraints. The most common is to define the cartesian space as a set of translations in three-axis and the rotation over the same axis. Hence, is possible to identify a well resolved linear function between joints and cartesian representation as long as there are no external factors (such as wrist offsets).

One way to explore the inverse kinematics of this kind of robots is using a geometrical approach, where we can decompose a robot in parts as long as the wrist is spherical. To properly explain the usage of inverse kinematics, there will be presented an example already explored in previous works by Tavares (2015). The selected robot, in the mentioned work, was the Universal robot 5 (UR5) (see Figure 3.1), a collaborative robot, that fits the concept of 6-DOF robots with a spherical wrist. In this case, it is a robot with a set of six revolute joints.

Figure 3.1: Universal Robot 5 (UR5)

The first step is to determine the kinematic equation of this robot. In that regard, it was created a table with the important information on the relation between joints accordingly to the DH method (see Table 3.1 and Figure 3.2).

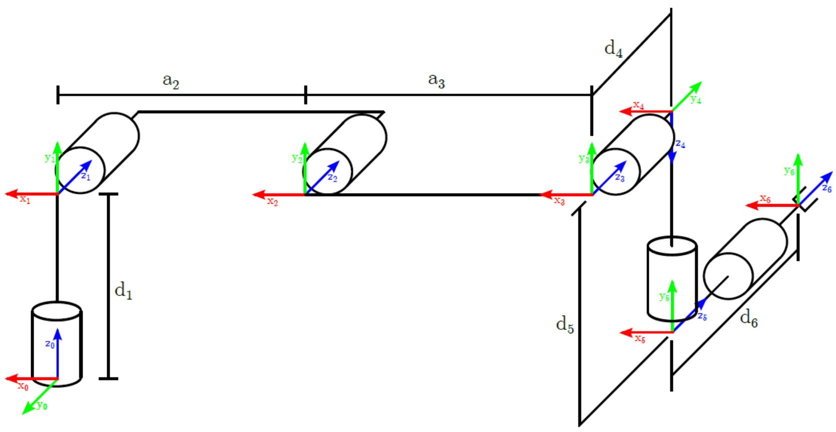


Figure 3.2: Kinematic Referential for the UR5 (Keating)

Table 3.1: UR5 DH Parameters

Joint	a_i	α_i	d_i	θ_i
1	0	π / 2	d_1	θ_1
2	-a_2	0	0	θ_2
3	-a_3	0	0	θ_3
4	0	$\pi/2$	d_4	θ_4
5	0	-$\pi/2$	d_5	θ_5
6	0	0	d_6	θ_6

For this particular robot, the first step is to determine the value of θ_1. For that purpose it is required to consider the fifth robot joint and its position when compared to the robot origin (P_5^0). Thus, there is a need to translate the global transformation back to the fifth joint. This is a translation along the z-axis with a known value of -d_6. Based on the previously presented equation 3.2 e 3.3, it is possible to determine:

$$P_5^0 = T_6^0 * \begin{bmatrix} 0 \\ 0 \\ -d_6 \\ 1 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{3.4}$$

From a top perspective of the UR5 we have (in Figure 3.3):

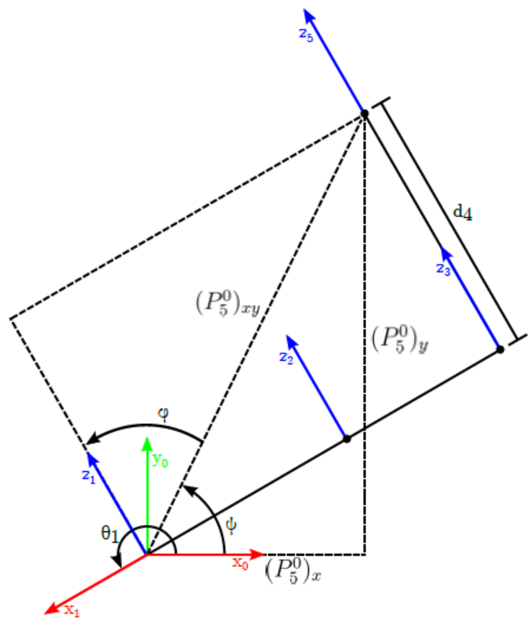


Figure 3.3: Top perspective of the UR5 (Keating)

Having the position of the fifth joint, (P_5^0), the value of θ_1 can be defined as:

$$\theta_1 = \psi + \phi + \frac{\pi}{2} \tag{3.5}$$

$$\psi = atan2((P_5^0)_y, (P_5^0)_x) \tag{3.6}$$

$$\phi = \pm arccos\left(\frac{d_4}{\sqrt{(P_5^0)_x^2 + (P_5^0)_y^2}}\right) \tag{3.7}$$

Once determined θ_1, it is possible to determine θ_5. Once again, using the top perspective (including also the six joint this time), it is possible to express the resultant point of the transformation (P_6^0) as a direct dependency of θ_5 (see Figure 3.4).

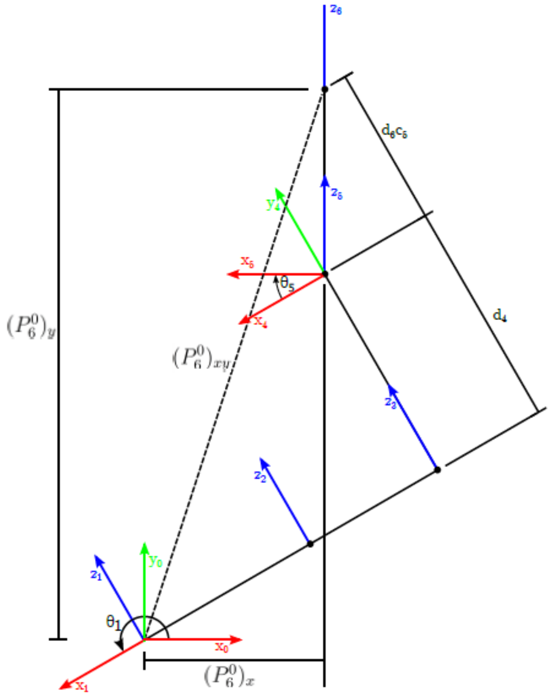


Figure 3.4: Complete top perspective of the UR5 (Keating)

$$(P_5^0)_x * sin(\theta_1) - (P_5^0)_y * cos(\theta_1) = d_6 * cos(\theta_5) + d_4 \tag{3.8}$$

$$\theta_5 = \pm arccos\left(\frac{(P_5^0)_x * sin(\theta_1) - (P_5^0)_y * cos(\theta_1) - d_4}{d_6}\right) \tag{3.9}$$

Based on equation 3.2, it is possible to define a transformation between joints 1 and 6 (T_6^1) as the product of $(T_1^0)^{-1}$ e T_6^0. Using equation 3.3, it is possible to connect the third column of the matrix T_6^0 with the values of θ_5 and θ_6:

$$-sin(\theta_6) * sin(\theta_5) = (T_6^1)_{1,2} \tag{3.10}$$

$$cos(\theta_6) * sin(\theta_5) = (T_6^1)_{0,2} \tag{3.11}$$

$$\theta_6 = atan2\left(\frac{-(T_6^1)_{1,2}}{sin(\theta_5)}, \frac{(T_6^1)_{0,2}}{sin(\theta_5)}\right) \tag{3.12}$$

Having the values of these joints, it is possible to apply the decoupling principle to redefine this manipulator as a planar manipulator with two revolute joints (Figure 3.5).

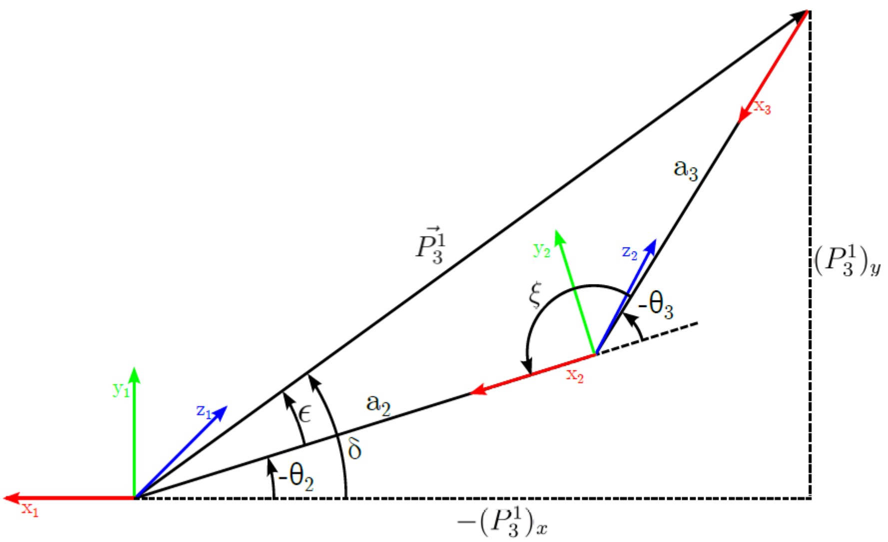


Figure 3.5: Joint decoupling Keating

As expressed in Figure 3.5, it is possible to define θ_3 based on P_3^1 and the values of a_2 e a_3:

$$cos(\xi) = -cos(\pi - \xi) = -cos(-\theta_3) = cos(\theta_3) \tag{3.13}$$

$$cos(\xi) = \frac{\left\|P_3^1\right\|^2 - a_2^2 - a_3^2}{2 * a_2 * a_3} \tag{3.14}$$

$$\theta_3 = arccos\left(\frac{\left\|P_3^1\right\|^2 - a_2^2 - a_3^2}{2 * a_2 * a_3}\right) \tag{3.15}$$

The same figure allows to determine the equation to calculate θ_2. This angle can be defined as the inverse value of the subtraction between two angles (δ e ε):

$$\delta = atan2((P_3^1)_y, (P_3^1)_x) \tag{3.16}$$

Using the law of sines:

$$\frac{sin(\xi)}{\|P_3^1\|} = \frac{sin(\varepsilon)}{a_3} \tag{3.17}$$

$$\varepsilon = arcsin\left(\frac{sin(\xi) * a_3}{\|P_3^1\|}\right) \tag{3.18}$$

$$\theta_2 = -(\delta - \varepsilon) \tag{3.19}$$

Knowledge of all joints' values except the fourth joint make it easy to determine all the transformations between jointsT_j^i and from those withdraw the transformation T_4^3. Based on equation 3.2:

$$T_4^3 = T_1^3 * T_4^1 = (T_2^1 * T_3^2)^{-1} * T_1^6 * (T_5^4 * T_6^5)^{-1} \tag{3.20}$$

Isolating the first column of the matrix it is possible to calculate θ_4:

$$\theta_4 = atan2((T_4^3)_{1,0}, (T_4^3)_{0,0}) \tag{3.21}$$

The direct kinematic is also a consequential result of this method, thus, being possible to be represented as a set of analytic expressions. The transformation matrix can be defined as:

Table 3.2: Homogeneous Transformation Matrix

Transformation Matrix	$Column_1$	$Column_2$	$Column_3$	$Column_4$
$Line_1$	x_x	y_x	z_x	$(P_0^6)_x$
$Line_2$	x_y	y_y	z_y	$(P_0^6)_y$
$Line_3$	x_z	y_z	z_z	$(P_0^6)_z$
$Line_4$	0	0	0	1

For simplification issues, $cos(\theta_i)$ elements will be replaced by c_i and $sin(\theta_i)$ elements by s_i.

$x_x = c_6 * (s_1 * s_5 + ((c_1 * c_{234} - s_1 * s_{234}) * c_5)/2 + ((c_1 * c_{234} + s_1 * s_{234}) * c_5)/2) - (s_6 * ((s_1 * c_{234} + c_1 * s_{234}) - (s_1 * c_{234} - c_1 * s_{234})))/2;$

$x_y = c_6 * ((s_1 * c_{234} + c_1 * s_{234}) * c_5)/2 - c_1 * s_5 + ((s_1 * c_{234} - c_1 * s_{234}) * c_5)/2) + s_6 * ((c_1 * c_{234} - s_1 * s_{234})/2 - (c_1 * c_{234} + s_1 * s_{234})/2);$

$x_z = (s_{234} * c_6 + c_{234} * s_6)/2 + s_{234} * c_5 * c_6 - (s_{234} * c_6 - c_{234} * s_6)/2;$

$y_x = -(c_6 * ((s_1 * c_{234} + c_1 * s_{234}) - (s_1 * c_{234} - c_1 * s_{234})))/2 - s_6 * (s_1 * s_5 + ((c_1 * c_{234} - s_1 * s_{234}) * c_5)/2 + ((c_1 * c_{234} + s_1 * s_{234}) * c_5)/2);$

$y_y = c_6 * ((c_1 * c_{234} - s_1 * s_{234})/2 - (c_1 * c_{234} + s_1 * s_{234})/2) - s_6 * (((s_1 * c_{234} + c_1 * s_{234}) * c_5)/2 - c_1 * s_5 + ((s_1 * c_{234} - c_1 * s_{234}) * c_5)/2);$

$y_z = (c_{234} * c_6 + s_{234} * s_6)/2 + (c_{234} * c_6 - s_{234} * s_6)/2 - s_{234} * c_5 * s_6;$

$z_x = c_5 * s_1 - ((c_1 * c_{234} - s_1 * s_{234}) * s_5)/2 - ((c_1 * c_{234} + s_1 * s_{234}) * s_5)/2;$

$z_y = -c_1 * c_5 - ((s_1 * c_{234} + c_1 * s_{234}) * s_5)/2 + ((c_1 * s_{234} - s_1 * c_{234}) * s_5)/2;$

$z_z = (c_{234} * c_5 - s_{234} * s_5)/2 - (c_{234} * c_5 + s_{234} * s_5)/2;$

$(P_0^6)_x = -(d_5 * (s_1 * c_{234} - c_1 * s_{234}))/2 + (d_5 * (s_1 * c_{234} + c_1 * s_{234}))/2 + d_4 * s_1 - (d_6 * (c_1 * c_{234} - s_1 * s_{234}) * s_5)/2 - (d_6 * (c_1 * c_{234} + s_1 * s_{234}) * s_5)/2 + a_2 * c_1 * c_2 + d_6 * c_5 * s_1 + a_3 * c_1 * c_2 * c_3 - a_3 * c_1 * s_2 * s_3);$

$(P_0^6)_y = -(d_5 * (c_1 * c_{234} - s_1 * s_{234}))/2 + (d_5 * (c_1 * c_{234} + s_1 * s_{234}))/2 - d_4 * c_1 - (d_6 * (s_1 * c_{234} + c_1 * s_{234}) * s_5)/2 - (d_6 * (s_1 * c_{234} - c_1 * s_{234}) * s_5)/2 - d_6 * c_1 * c_5 + a_2 * c_2 * s_1 + a_3 * c_2 * c_3 * s_1 - a_3 * s_1 * s_2 * s_3);$

$(P_0^6)_z = d_1 + (d_6 * (c_{234} * c_5 - s_{234} * s_5))/2 + a_3 * (s_2 * c_3 + c_2 * s_3) + a_2 * s_2 - (d_6 * (c_{234} * c_5 + s_{234} * s_5))/2 - d_5 * c_{234}.$

From the inverse kinematics analysis is also possible to identify eight different paths to a goal solution. Each one represents a different robot configuration. Considering the most common manipulator (anthropomorphic manipulator) these are usually the number of solutions. At each pose (position and orientation), the robotic arm can assume different configuration based on the shoulder, elbow and wrist configuration (Figure 3.6).

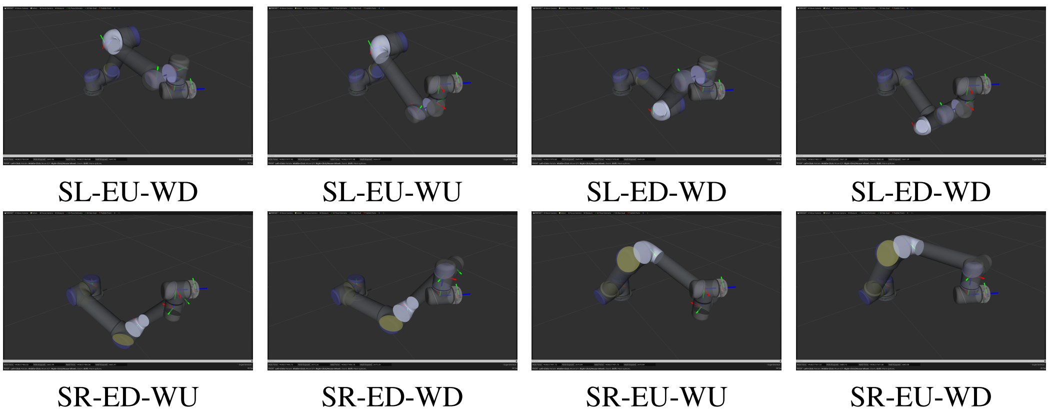


Figure 3.6: UR5 different configurations; SL - shoulder left, SR - shoulder right, EU - elbow up, ED - elbow down, WU - wrist up, WD - wrist down (Tavares et al. (2016))

Many aiding tools have been developed already to cope with this kind of robot systems. One of which, presented by OpenRAVE (2015) is getting an acceptance by the robotic community as it provides a service (IKFast) that analytically analysis a geometrical file (COLLADA) to determine the set of solutions for the robotic systems.

3.1.2 Non-Standard Robotic Systems

Recently many robots have been developed with some mechanical deviations when compared to traditional 6 revolute DOF industrial manipulators (such as the one presented in the previous subsection). Either for better process completion or to comply with pre-defined constraints such as collaborative work, there is a clear shift from a mass production of common robots to personalized robotic fabrication. Examples of these robots are displayed in Figure 3.7.

Figure 3.7: Personalized mechanical robot configuration: left - Yaskawa MPX3500; right - Kuka IIWA

On the previous figure, it is possible to identify two uncommon industrial robots. The first one, Yaskawa MPX3500, has a wrist offset which is optimal for coating procedures, while the second, Kuka IIWA, is a designed lightweight robot ideal for human-robot collaboration.

As defended by Liu et al. (2012), *there are no practical closed-form inverse kinematics solutions for 6-DOF serial robot manipulators with offset wrist*. Therefore its kinematic calculation requires a shift from the geometrical / analytic methods to iterative methods. Wu et al. (2015) and Pashkevich (1997) among others have already tried to present a solution for robots with a non-spherical wrist. Another innovative approach is to use advanced algorithms to solve this problem. In this regard, Kalra et al. (2003) proposed a genetic algorithm as a possible approach.

Another crucial development from the scientific community on robotic kinematic is related to kinematic compensation. This may be one way to go, as the correction of the kinematic parameters may be scaled to kinematic parameters finding. Some studies on this topic have already been validated by the scientific community, with some examples being: Du et al. (2015a,b).

Despite its relevance, there is still no unified approach for this particular robots. Some methods may be scaled and modified to serve other kind of robots, such as the collaborative robotic area, however there is no standard tool such as the IKFast for these robots.

3.2 Dynamics

The kinematics of a robot is established using no dynamic constraints. Therefore, perfect exercise involves direct relation between joint's values and robot position. Notwithstanding, a crucial aspect concerning robot motion is the dynamic effect of such motion.

Therefore, the evaluation of poses' dynamic stability is key. Parameters such as singularities, robots' velocity and effort should be taken into account when trying to control any given robot. To this regards, the Jacobian matrix of a robotic solution gains importance. This matrix defines the dynamic relationship throughout separate states of the robot (which can be the poses to handle).

The Jacobian matrix is the resulting matrix of all the first-order partial derivatives of a given vectorial function. In robotics, the Jacobian of a robot can be define as the the first derivative of the kinematic equations. Let's assume θ_t as the function of the N joints of a given robot joints through time and x_t as the cartesian position of the robot through time. The Jacobian (J) can be defined as:

$$\dot{x_t} = \mathbf{J} * \dot{\theta_t} \tag{3.22}$$

Considering a position x as a set of cartesian translation and rotations defined from now on as the cartesian traslation (x,y,z) and the orientation rotation (w,p,r), its derivative will generate the velocity of a given manipulator at any given time. From deriving x, we have:

$$\dot{x_t} = \dot{\begin{bmatrix} x \\ y \\ z \\ w \\ p \\ r \end{bmatrix}} = \begin{bmatrix} v_x \\ v_y \\ v_z \\ w_x \\ w_y \\ w_z \end{bmatrix} \tag{3.23}$$

Here is possible to identify two different velocities group. The linear velocity across an axis (v_x, v_y, v_z) and the angular velocities around the axis (w_x, w_y, w_z). This separation allows to divide the Jacobian also in two parts: linear and angular:

$$J = \begin{bmatrix} J_v \\ J_w \end{bmatrix} \tag{3.24}$$

Focusing first on angular section, it is important to acknowledge that for revolute joints, the rotation is around the z_{i-1} axis and the angular velocity may be express as:

$$w_{i-1,i}^{i-1} = \dot{\theta}_i * z_{i-1}^{i-1} = \dot{\theta}_i * k \tag{3.25}$$

With k, being a normalized vector along z-axis. For prismatic joints this value is naturally null. Knowing that:

$$w^0_{0,n} = w^0_{0,1} + R^0_1 * w^1_{1,2} + ... + R^0_{n-1} * w^{n-1}_{n-1,n} \tag{3.26}$$

It is possible to infer that the value for each parcel for the angular velocity Jacobian (J_w) can be given by:

$$J_w * \dot{\theta} = \lambda_1 * \dot{\theta}_1 * k + \lambda_2 * \dot{\theta}_2 * R^0_1 * k + ... + \lambda_n * \dot{\theta}_n * R^0_{n-1} * k \tag{3.27}$$

$$J_w * \dot{\theta} = \lambda_1 * \dot{\theta}_1 * z^0_0 + \lambda_2 * \dot{\theta}_2 * z^0_1 + ... + \lambda_n * \dot{\theta}_n * z^0_n \tag{3.28}$$

In each case λ_i is 1 for revolute joints and 0 for prismatic ones.

Then, the linear section of the Jacobian is given by the sum of partial derivates of motion in terms of joint motion. Therefore it is possible to define v^0_n as:

$$v^0_n = \frac{\partial x^0_n}{\partial \theta_1} * \dot{\theta}_1 + \frac{\partial x^0_n}{\partial \theta_2} * \dot{\theta}_2 + ... + \frac{\partial x^0_n}{\partial \theta_n} * \dot{\theta}_n \tag{3.29}$$

$$J_v = \begin{bmatrix} \frac{\partial x^0_n}{\partial \theta_1} & \frac{\partial x^0_n}{\partial \theta_2} & ... & \frac{\partial x^0_n}{\partial \theta_n} \end{bmatrix} \tag{3.30}$$

Once again the determination for prismatic and revolute joints differ. Using Figure 3.8 as visual-aid it is possible to define the relation for prismatic joints:

$$\dot{x^0_n} = \dot{d}_i * z^0_{i-1} = \dot{d}_i * R^0_{i-1} * \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{3.31}$$

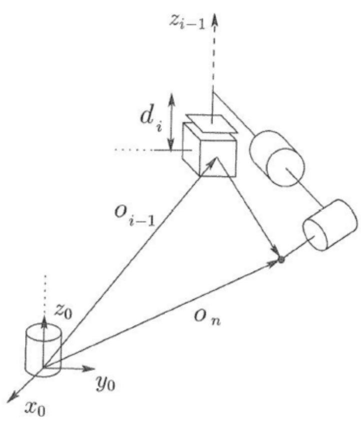


Figure 3.8: Linear velocity Jacobian prismatic helper (Moreira (2013))

Using Figure 3.9 as visual-aid it is possible to define the relation for revolute joints:

$$\dot{x_n^0} = w_t * r = \dot{\theta}_i * z_{i-1}^0 * (x_n^0 - x_{i-1}^0) \tag{3.32}$$

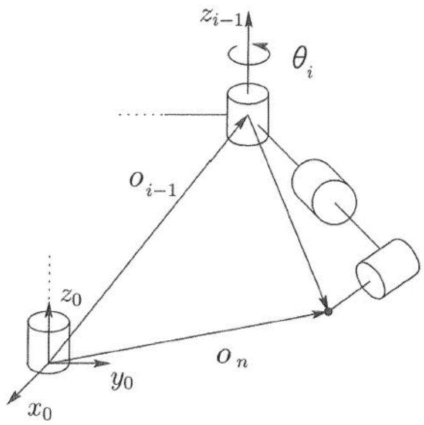


Figure 3.9: Linear velocity Jacobian revolute helper (Moreira (2013))

The analysis of the Jacobian is rather relevant for the dynamic analysis of a given motion. Once obtained the Jacobian for the required movement its analysis gives information on possible singularities, joints mechanical efforts and manipulation ranges.

The robot singularity occurs when the robot loses its ability to move the end effector in a given direction no matter how the next joint state is defined. Normally it occurs when two of the robot's joint are aligned making them redundant. By analyzing the Jacobian, it is possible to identify these issues simply by determining whether its columns are independent or not. When the columns lose independence the robot is facing a singularity.

The mechanical effort, torque, of each joint is Jacobian-dependent as well. Assuming a vector $\vec{F}$, defining the force applied by the robot's end-effector, it is possible to define the torque of each joint, T as:

$$\mathbf{T} = \mathbf{J^T}(\theta) * \tilde{\mathbf{F}} \tag{3.33}$$

At last, the manipulation capability (μ) of a robot is defined by the determinant of the Jacobian matrix:

$$\mu = |det(\mathbf{J})| \tag{3.34}$$

When the value is null, the robot is facing a singularity and its manipulation range is therefore nonexistent. The higher the value of the determinant the higher is the motion range for a given robot.

3.3 Chapter Summary

In this chapter, the mathematics associated to robot motion and control were explored in detail. To date, it is possible to identify clear analytic relations between cartesian poses and robots' joint state for robots with no wrist offset and 6DOF. Higher DOF robots require a numerical approach. The dynamics associated with the robot movement is also well documented and through the determination of a Jacobian, it is possible to infer on any given robot state.

Despite all the efforts, there are still some limitations, especially when facing non-traditional robots, with higher DOFs or new mechanical designs. These problems are still a field to be explored and lack a standard solution.

Part II

Implemented Design

Chapter 4

Software Framework

The focus of this thesis is to develop and apply an optimization algorithm to real industrial facilities. In order to achieve that, a set of software auxiliary tools are required to complete the information cycle from project designer to shop floor operator. These tools explored in this thesis are presented below.

In Section 4.1, a user-developed simulator that intends to mimic a real industrial environment is presented. Then, in Section 4.2, a software for automatic vector generation is described. This software is the commercial bridge between high-level part design and development and low-level manufacturing proposed by SARKKIS robotics.

4.1 Digital-Twin Simulator

Simulation software is an important tool to both research and industrial communities. The usage of such tool provides a dynamic virtual view and testing of a shop floor workcell or an individualized system, while avoiding damaging such system. Petrovic et al. (1998); Collins et al. (2001); Craighead et al. (2007) showed a wide range of simulation solutions ranging from control models testing, to semiconductor manufacturing or even vehicles dynamic study.

In robotics, the usage of simulators can provide relevant information on a given challenge. As explained by Harris and Conrad (2011); Kumar and Reel (2011), the efforts in generating new frameworks and tool kits to help bring robotics simulation to a one-to-one relationship with real-world interaction have resulted in a set of simulators that provide a better insight in a real workcell system, thus saving time and financial efforts.

Today, it is possible to find multiple software solutions, which allow an in-depth study over small sections of the overall robotic system, such as robot kinematics, workcell positioning or even workcell calibration. Examples of these software are the RoboDK, RoKiSim or COSIMIR, which allow the user to explore these possibilities through a visual interaction with a 3D model (RoboDK (2015); COSIMIR (2011)).

In addition, is important to integrate these tools with the usage of exterior sensors or devices, such as, Programmable Logic Computers (PLC) or sensors. Veiga et al. (2009); Valera et al. (2012) discussed this integration in their scientific work.

A recent and fast growing solution that promotes modular implementations has been proposed based on the robotic operative system (ROS) and its associated simulator Gazebo, as well as Visual Components software. These allow for the simplification of most problems by developing multiple simple algorithms that, when integrated, assure a modular solution to a complex problem while adding flexibility to the overall system.

Industry 4.0 represents a novel concept that includes cyber-physical systems and Internet of Things (IoT). Within this industrial trend, notion of *Digital Twins*, virtual substitutes of real world objects, has gained considerable importance in the field of robotics. The ability to exactly mimic the industrial environment throughout all process allows an operator to remotely inspect and follow the operation. Furthermore, simulators can be integrated as iterative tools to achieve program optimization for a given workcell as proposed by Schluse and Rossmann (2016); Boschert and Rosen (2016).

The robotic simulator developed in this thesis (Tavares et al. (2018)) has already obtained scientific validation. As stated in the article, *the main goal of this work is to develop a flexible simulation solution to be used by present and future robotic and automated workcells. The proposed solution fits the requirements enumerated above, while being able to communicate with any external devices using generic protocols. In addition, it can also reproduce jobs and tasks of any dynamic workcell designed for the simulator*.

The selected implementation structure is the paradigm of Model-View-View Model (MVVM). This architecture is divided into three major layers: (1) the View, which is the graphical structure that serves all user interfaces (UI), (2) the View Model, which is the programmable section of software that manages properties and commands to be displayed or raised by bindings with the View, and (3) the Model that represents the real content of a defined object (see Figure 4.1).

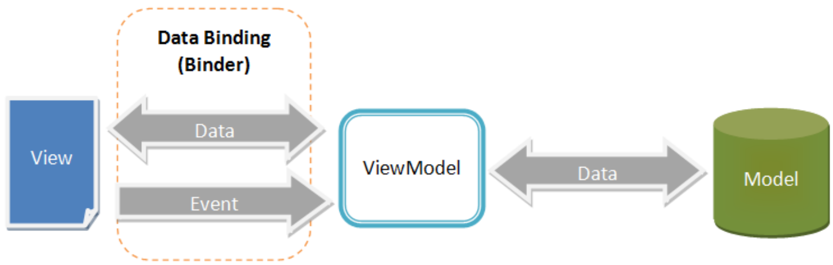


Figure 4.1: MVVM Architecture Schematic

To cope with industrial requirements, while allowing for a stable and user friendly simulation solution, the segmentation of the overall software is important. Using MVVM, it is possible to create information modules for 3D visualization, communication, information storage and, obviously, simulation, among others. These will be discussed in the chapter subsections presented below.

4.1.1 3D Visualization

An important aspect of any simulator is its user interface. Thus, a 3D engine able to render the entities of structures to be displayed was selected for this work, and the software Eyeshot Ultimate was used (Eyeshot (2017)).

The Eyeshot Ultimate software is based on the construction of geometries (e.g. Mesh, surfaces, solids, lines or just profile extrusions) which are associated to major blocks, recursively inserted within other blocks in order to recreate a geometrical chain. This methodology is easily integrated with automated and robotic workcells where there may exist a tool attached to a robot placed on top of an external axis, or simply a machine structure with tools placed in key positions. For a detailed recreation of the work place, it is possible to place separate blocks containing walls, tables or even human operators geometry details, thus, completing the work environment.

Another crucial aspect of a 3D engine built with Eyeshot Ultimate 10 is the ability to animate all attached blocks given a normalized axis transformation. Thus, it is possible to recreate robots/parts movements by crossing the axis information at each joint with this animation feature. Additionally, similar to all 3D engines, Eyeshot has the rotate/translate view features that allow a better grasp of the recreated cell, as well as, a unique feature of dragging and dropping components (Object Manipulator) that provides an inexperienced user with a wide range of validation tools (from re-positioning parts to visualizing better displays for such parts).

An example of a high redundancy robot-based system developed on Eyeshot can be found below (see Figure 4.2).

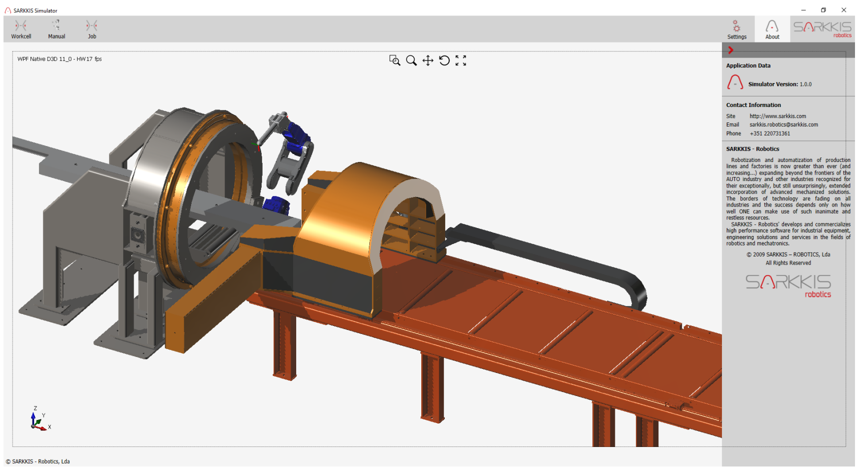


Figure 4.2: Example of a robotic workcell - SARKKIS robotics simulator

4.1.2 Communication Channels

In order to integrate external devices with the simulator, two major connection channels were created: Modbus TCP/IP and Ethernet IP.

The Ethernet IP is a standard protocol that uses the potential of Ethernet communication to send UDP packages that contain basic Input/Output data.

The Modbus TCP/IP consists in Modbus RTU (Remote Terminal Unit) protocol with a TCP interface running on Ethernet. Modbus RTU is an application protocol, as it defines rules for organizing and interpreting data, but consists in a messaging structure, independent of the underlying physical layer. Essentially, Modbus TCP/IP combines a physical network (Ethernet), with a networking standard (TCP/IP), and a standard method of representing data (Modbus as the application protocol).

To validate the communication between controllers and the simulator, it was parametrized a soft PLC using the development system 'Codesys', compliant with the IEC 61131-3 standard. The main goal of it is to control all the operations regarding the simulation of the beam drilling and sawing machine shown along the controller's HMI on Figure 4.3.

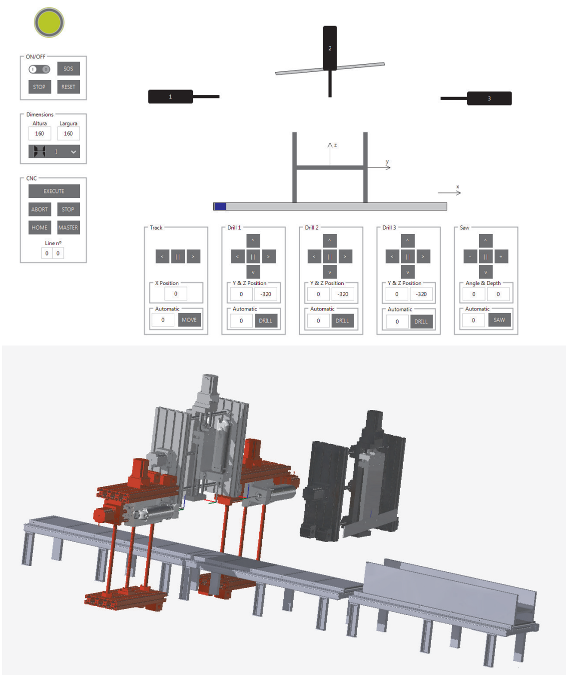


Figure 4.3: Beam drilling and sawing machine simulation & the respective HMI

With that goal in mind, the PLC can not only command and control all the manual and semi automatic operations activated using the features presented on the HMI, but also execute CNC programs generated by a CAM software for the production of beams, generating text files containing G Code that are subsequently read and interpreted by the controller. After interpreting the G Code, the controller determines which axes are to be moved and controls their movement with position related feedback.

In order to simulate the control of a beam drilling and sawing machine, the PLC communicates the actual position of the motors with the simulator using Modbus TCP/IP.

A Modbus TCP/IP server was created on the soft PLC and a client on the simulator. On the server side, by using 'Codesys' for the controller's development there is only the need for setting the parameters needed for the communication to work, as 'Codesys' has already the Modbus

TCP/IP protocol entirely implemented. On the client side, the parameters were set so the communications works seamlessly.

Overall, this system allows the user to test the machine's controller and visualize its behaviour and sequence of commands, helping on its implementation on a later phase.

4.1.3 Modular workcell Deployment

The modular workcell construction allows for selection of individual components from a database or for the use of acceptable files, followed by assembly of these to form chains.

In order to insert a component, the system requires a generic language document that follows a combination of Unified Robot Description File (URDF) and Simulation Description File (SDF) standards with some minor adjustments.

SDF files require a global knowledge of the work chain, while URDF files only represent a single component of such chain. The file type defined as generic input of this simulator serves both worlds, as it allows to create from single objects description files to complete work chains. It is accomplished by defining components of interest for each file, its relations and possible future transformations points that may link the chain described on one file with the following ones.

Then, to better organize the insertion and allocation process, five major types of components were selected:

1. External Structures: comprehending any structure that can be linked to other components such as robotic external axis or CNC machinery.

2. Robots: a large database of robots is associated to the software and the possibility of linking others by creating an URDF based file is presented to the user (example on Figure 4.4).

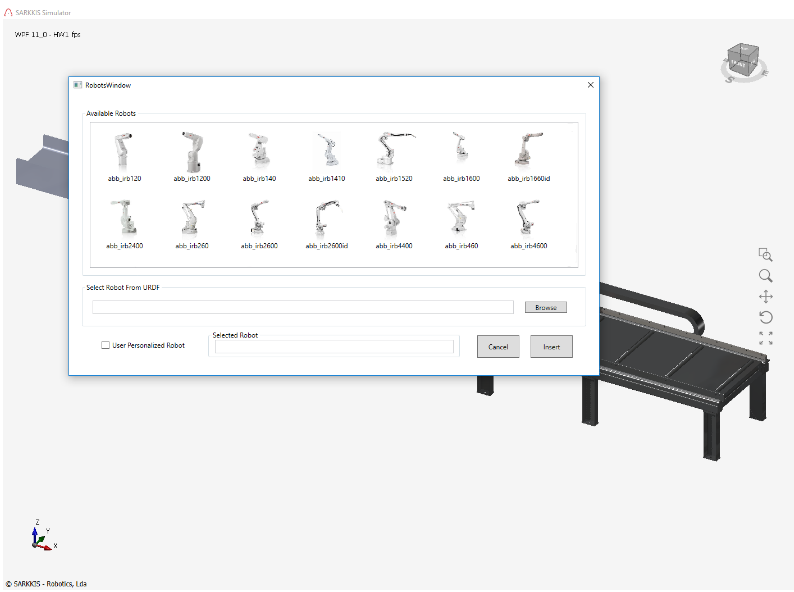


Figure 4.4: Example of Robot Choosing Window

3. Tools: comprehending lasers, grippers, visual attachments, other sensors or a plain combination of all the above.

4. Fixed Items: components that simply give a more detailed aspect to the simulation environment and may serve as frame referential or components' support.

5. Moving Items: parts that may move separately from the rest of the chain or that may insert some motion on attached components without moving themselves, such as conveyors.

Once all components are inserted in the workcell, it is possible to remove, replace or reposition them. Moreover, the linkage between components is defined using context menus where it is indicated whether or not a component should be inserted within a block of a previous component.

4.1.4 Robot / Machinery / System Motion

Another key aspect of a simulator is its animation, i.e. what kind of movement it is able to recreate. Taking into consideration that the proposed simulator intends to serve all industrial workcells, a generic language to represent differential motion events, such as, linear or joint movements for robotic cells, position shifts for conveyor's parts as poses transformations for objects associated with common machinery (drill, saws, torches attached to linear axis...) was created.

A kinematic algorithm (similar to IKFast from OpenRAVE) was also developed in order to fully describe the chain kinematics whether it may be a robotic work chain or a common work chain. This algorithm is based on the robot model data withdrawn from the software. From the consecutive transformation between joints, it is possible to infer the robot parameters and from those it is possible to describe its kinematic equations.

For a 6-DOF robot with spherical wrist this is very straightforward and an analytic expression can be used. Nevertheless for custom robot, with wrist or body offsets as well as robots with more than 6-DOF, this analytic expression is not available. In these cases, a numeric algorithm was created considering each joint transformation and with a number of equations to be optimized scaling with the number of joints. This methodology is simply the application of equations 3.1, 3.2 and 3.3 from section 3.1 with a twist of considering an extra offset transformation for each robot joint. Then, applying an adaptive least squares method it is possible to complete the kinematic cycle.

Complementary to this algorithm, the simulator suggest a wide range of path planner options, both complete and optimal, such as the A* family, or probabilistic. Each option has its advantages and disadvantages, and, thus, considerations should be made on which to be used for a given case.

Essentially, the simulator grants the user the option to test and validate poses and movements manually or by using predefined planners.

4.1.5 Task / Job Loading and Testing

Manufacturing processes typically start with a design project of a part to be produced. Based on that project some information may be withdrawn in order to sequence a set of points and operations to be performed in an initial part in order to convert it to the projected one.

The idea behind this simulator is to accept multiple project formats, decrypt them and identify what positions and operations are coded within that project. Currently it is accepted both cutting and welding tasks or jobs (set of tasks). Then, the decrypted files create a list of instruction to be graphically reproduced on the simulator.

The interaction with the simulator user is important and this list must provide enough information so that such user is able to identify operation sequence and its possible bottlenecks, being able to act on the setback and plan a cleaner operation flow. Furthermore it is also possible to infer the status of system outputs by analyzing the list of instructions which provides a greater overview on the operation procedure.

The paradigm of digital twin simulation is crucial to follow the real system motion and behaviour. Furthermore, the usage of this particular simulator allows not only to follow the system behaviour but also to preview it, defining efficient robotic sequences that will untimely increase manufacturing productivity in real world workcells. This simulator was used as a virtual validation tool of some highly complex robotic cells. The first robotic cell was developed under the CLARiSSA European Project (see Figure 4.5).

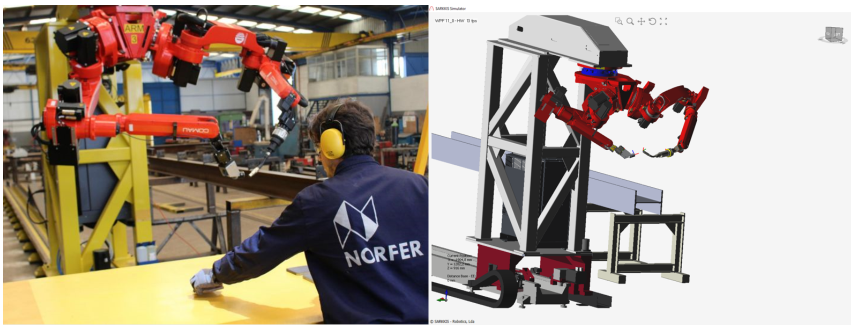


Figure 4.5: Example of loaded and decrypted Job.

The simulator is of crucial importance since it allows for the robotic code to be interpreted by the simulator leading to a sequence of actions. Each action was validated with the simulator platform and, once finished, a new robotic code was generated in order to be applied to the robotic workcell.

Thus, this simulator is able to provide the user with new and flexible state-of-the-art tools, such as optimization techniques. It represents a key framework to be considered for future robotic applications.

4.2 Vector Generation Software

Another important software to complete the overall cycle for manufacturing is the commercial CAM software from SARKKIS robotics. This software imports 3D model files, such as DSTV or DWG and mainly IFC and generates important process parameters.

The steel fabrication industry has been using file formats with limited information to manage the production cycle. These limitations have great impact in how the information flows at the shop floor level, increasing the probability of human error and affecting the quality of the products produced by the company.

The Building Information Modeling (BIM) term was first introduce by van Nederveen and Tolman (1992) and refers to a building design methodology characterized by the generation and use of coordinated and internally consistent computable information about a building project in design and construction.

Despite of the high added value related to the standardization of information throughout all stages of the steel fabrication process, a correct definition of such standard is still debatable. Over the years, the DSTV file was the main file format used in the production process, but the limitations in both geometrical descriptions and additional information to vertically connect design and production stages, raises the need for a more complete file format.

Over the last few years, we have been noticing a clear effort towards improving such conditions while assuring the interoperability between all key processes and partners required to perform a given task.

These efforts lead to the creation of an ISO standard for data modeling - the IFC developed by buildingSMART (buildingSMART (2019)). Up until recently, the IFC based work flows are more commonly seen in the design phase of the building projects, being less available for the fabricators. Despite being a data modeling strategy not completely exploited yet, it shows some interesting characteristics as it allows the creation of an automated information flow between design and production. Furthermore, the IFC can describe the complete design and production process in a unique file, simplifying the integration between teams and companies.

IFC data model is a file format specification that intends to unite both ends of the process and facilitate interoperability in the architecture, engineering and construction (AEC) industry. The IFC model specification is open, available and registered by ISO as an official International Standard ISO 16739:2013. It is an object-based file format with a data model developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) and is a commonly used collaboration format in Building Information Modeling (BIM) based projects (Succar (2009)).

In the following subsections the information processing cycle will be presented starting with the 3D model file creation using processing tools in the CAM software of SARKKIS.

4.2.1 IFC creation

Throughout this project, the Tekla software was used for handling CAD and BIM information. Tekla Structures (TS) is the building information modelling software (3D detailing) that has been the reference source of BIM information from which *.ifc format files are obtained and used for production. It was chosen due to its widespread usage in the construction industry (specially steel construction).

The steps to obtain, from TS, the ifc file for a given structure / assembly are fairly straight forward and use Tekla's own IFC export system. Nevertheless some small steps need to be in place prior to export so that all important information is obtained. These sequences are done by activating Tekla's functions in order to properly export a set of crucial operation parameters.

The output is a IFC file containing all relevant information for the project execution that then is made available for production. Once again, this is a specific approach to Tekla Structures IFC export procedure, known at the moment, expecting that similar BIM modelling applications will generate similar data output.

4.2.2 IFC Parser

Parsing IFC files is not an easy task to accomplish given its complexity and flexibility. The buildingSMART (buildingSMART (2019)) organization provides all the tools and information required to do it, but the complex definition of the elements, the hierarchy and the relation of each other inside the file make this a complex task.

Currently there is an extensive offer of alternatives, free or commercial parsers like the OpenBIM (OpenBIM (2019)) or some of the toolboxes of parsers that can be found on buildingSMART website or IFCWiki (Wiki (2019)) for example. This can be a boost for the integration process but will not be enough for software development, requiring some knowledge of the IFC hierarchy to know were you can find in the file the properties that you need for the software development.

4.2.3 IFC Information Processing

Once the IFC data is parsed and transformed into usable information, it is given to the CAM software (developed by SARKKIS - Robotics) for generating vectors of interest for performing a IFC defined weld operation. The automatic parsing and transformation of IFC data into usable information for programming a welding robot is a huge improvement in the fabrication process, not only for offline programming but also for the traceability of the process (dimensions, materials used, finishes) due to no longer being necessary to be manually done by an operator.

Looking into to the MetroID BeamWeld software, the weld information can dramatically speed up the preparation of the welding operations, since it is no longer necessary to manually detect the joints to be welded within the CAD models. Using the IFC CAD data and weld specification it is possible to automatically generate the welding vectors shown in Figure 4.6. For achieving this, advanced algorithms were developed for detecting the joint line and ensure collision avoidance between the welding torch and the parts to be welded.

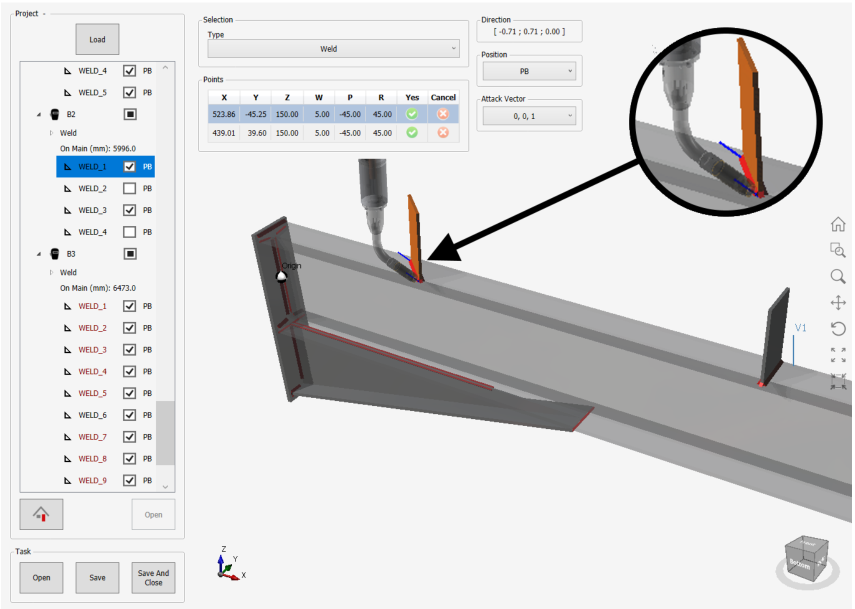


Figure 4.6: MetroID BeamWeld Software

Throughout this thesis the developed algorithms also targeted the CAM software from SARKKIS. The optimization of output vectors is assured by validating the tool path and placement over the originally generated points. The output difference are displayed in Figure 4.7.

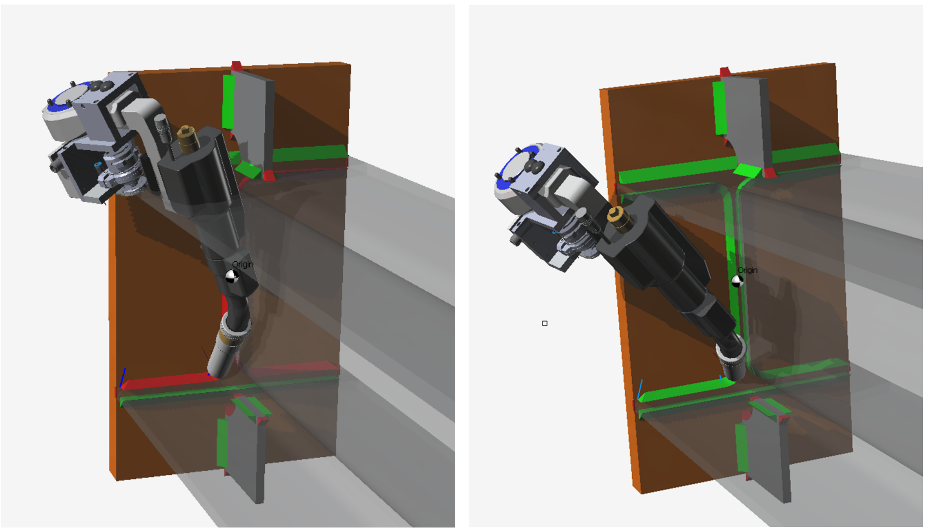


Figure 4.7: Correction of Output Vectors in SARKKIS CAM

Furthermore, some geometrical heuristics were also developed so that some invalid operations could be saved by majoring the percentage of operation completion. One example of this is the split of colliding welds in Figure 4.8.

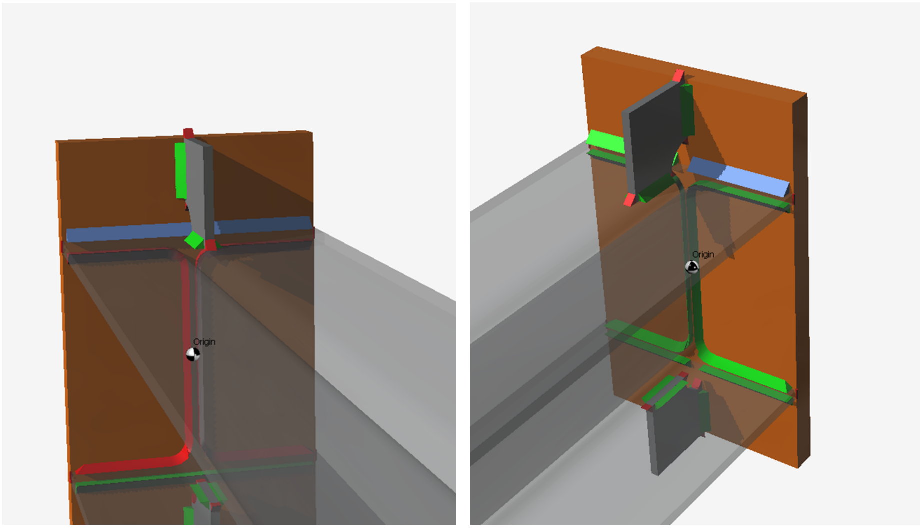


Figure 4.8: SARKKIS CAM weld splitting

4.3 Chapter Summary

In this chapter, a software framework base is presented focused on two of the virtual developing helpers for this thesis. First, it is presented a digital twin simulator developed entirely in the course of this thesis and, then, a CAM software by SARKKIS is presented. The changes made on this software allowed for the development of more robust software that present improved vector generation and adaptation to the procedure tool.

Chapter 5

Implemented Methodology

The proposed methodology intends to provide a viable solution for vertical integration from the corporation management decision of shop floor upgrade to technical design and control of an optimized workcell to reach the desired goals.

The information flow from decision to workcell and ultimately to system machinery and operators has been developed throughout the years to achieve a more efficient data transmission from high level tiers in a corporation to the low levels of production and manufacturing.

Another key part of smart manufacturing is related to automation along the several decision and execution stages of a workcell. Here, we propose a three layer solution that can be applied to decide the optimal workcell to achieve the defined objectives by the industrial entity.

The real application of the proposed solution intends to deal with layout and components constraints while validating the usage of the workcell to complete the required tasks. Thus, the proposed methodology is based on three key stages: design, setup and execution. Each stage is flexible enough to be applied to multiple scenarios. Furthermore, we defend a cascade integration of the three stages as one can function as a decision tool from the other.

Summing up, the design stage can be considered an high level application to decide which components to select for a given shop floor goal. However it requires an algorithm for optimal placement of those components, which can be provided by the setup stage. This intends to classify random positions for a selected list of components in order to maximize the efficient of the predefined tasks. The classification is based on workcell execution completion, and, therefore, an execution stage analysis is required. This classification following a multi parameter cost function.

In the next sections, there will be presented the key parameters used in the cost function that enabled this work (Section 5.1). Then, a comparison study for the implemented optimization methodologies is shown in Section 5.2. The concept structure opted to be used throughout this thesis is summarized also in that Section. Following this section, an overview on each layer is presented in Section 5.3.

5.1 Cost Function

The selected algorithms follow an ideology of heuristic-based solutions and share a common goal, the minimization of effort and maximization of present and subsequent robotic poses. In that regard, a cost function was developed based on seven features:

1. *External Axis Motion:* While performing a task, it is pretended to minimize the external axis movement as they may insert instability within the robotic system - *ExternalM*.

2. *Singularities:* Robots' behaviour becomes unstable during singularities, thus, they should be avoided - *Sing*.

3. *Dynamic Constraints*: Velocity and acceleration (consequently force as well) of a given robotic system must be taken into account to ensure task completion - *Dynamic*.

4. *Configuration Change:* Robots should whenever possible keep an original configuration posture to avoid sudden uncontrolled movements - *Cfg*.

5. *Joints' Effort:* Minimization of system effort smooths movement and protects components - *JtEffort*.

6. *Reachability:* The distance between robot's base and goal position should be minimized to increase the reaching probability for future poses - *Reach*.

7. *Joints' Limits:* Similar to the previous criteria, in order to increase the reaching probability of future poses, an ideal pose should maximize the interval between joint position and limits - *JtLimit*.

Thus, the cost function that untimely dictates the viability of a random pose results in a weighed sum and can be described using equation 5.1.

$$\begin{aligned} COST &= w_1 * ExternalM + w_2 * Sing + w_3 * Dynamic + \\ &\quad w_4 * Cfg + w_5 * JtEffort + w_6 * Reach + w_7 * JtLimit \end{aligned} \tag{5.1}$$

One final comment is related to the usage of the cost function when there is no available solution. In those cases the testing hypothesis is discard without even being weighed.

Although not all variables stated in the equation are continuous or linear, the cost function value is well defined in all its domain. That is accomplish by processing each feature separately as described below.

Figure 5.1 displays the graph model of most of the previous presented parameters.

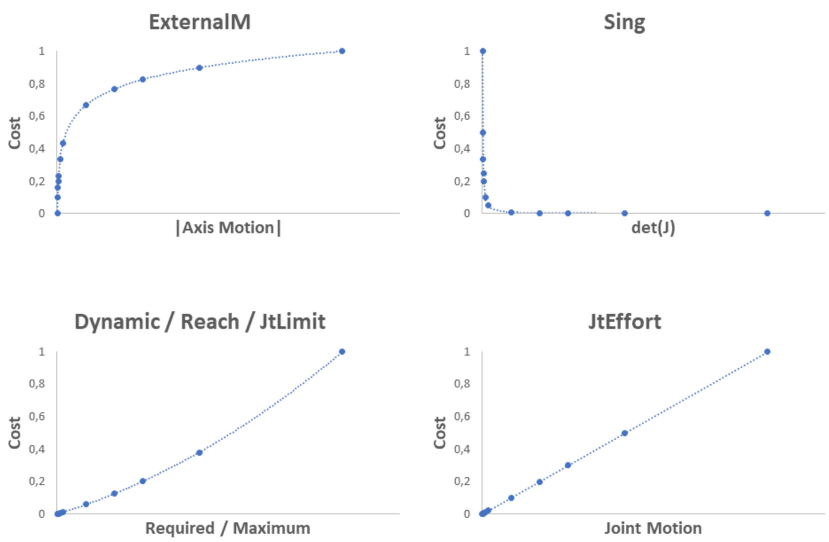


Figure 5.1: Graph Model for Most Cost Function Parameters

External Axis Motion can be classified using a logarithmic function. If the generated solution does not require external axis moves, the value *ExternalM* will be set to 0, otherwise it will be greater depending on the required motion. This parameter is either normalized by the external axis mechanical bounds if defined or by the external axis soft limits for a given trajectory. Furthermore the logarithmic growth is due to the instability of the motion, which is desirable to be avoid. Thus, there is a strong penalization on movement, while this penalization is capped to a maximum of 1, since the normalized cost curve tends to that value.

Singularities are determined and analysed using the robot Jacobian where its determinant is a indicator of singularities. When close to 0, the robot is approaching a singularity state. Thus, the inverse of that value (will be higher when closer to that singularity state) is used as the *Sing* parameter.

Dynamic constraints can be also evaluated using the jacobian. As presented in Chapter 3, Section 3.2, it is possible to infer whether the robot motion is comfortable or near failure. Once again the values for velocity effort, accelerations/forces are normalized based on system constraints. Then a mean between both conditions is applied and its value defines *Dynamic*.

Each robot manufacture has a configuration definition for a given joint state. Generically this is linked with the wrist-shoulder-elbow configurations. Ideally, when finding a new solution for a specified position, robots should avoid changing configuration as it prevents uncontrolled movements. *Cfg* is a binary value, 0 when configuration change is not require, 1 otherwise.

Regarding joints' effort, the weight associated to each joint is not linear since some joints have higher implications than other. Considering as an example, an anthropomorphic robot, the initial three joints' amplitude is more relevant than the wrist joints. Therefore the parameter *JtEffort* is obtained from a weighed sum with decreasing weight for each joint starting from base to end.

The *Reach* value is calculated based on the robot full length and is defined as the quotient between base to goal position distance and the full length value.

Finally, the joints' limits (*JtLimit*) follow the same pattern as the previous parameter, as it results from a quotient between estimated joint value and its limits. However, another layer is inserted here as for each joint the weight is different for similar reasons presented for the joints' effort parameter.

5.2 Optimization Methodologies

To face the proposed challenge there were selected four main optimization techniques: Linear Scanning, Genetic Algorithms, Simulated Annealing and Potential Fields.

Each of the proposed methods returns a heap storing the best outcomes of the cost function. Considering that each solution results in an array of joint values throughout the kinematic chain, a dynamic structure is built upon the map generation. Every heap element will follow the parameters defined within that same structure.

The reason behind using a multi-solution heap is related to the continuous path of the robotic system following the array of solutions. Even if a random position is validated and optimized, along the path between poses, there might be an extra constraint such as obstacles or speed effort. Thus, in those cases, the initial best solution has to be discarded and new one will be searched within the heap.

Each method also can be divided in two main phases: creation of hypothesis and validation. Since the idea is to find the optimal robotic system pose for a pre-defined position, the hypothesis initially focus the external axis values and then using a path planner validates and determines the robot positioning for those external axis values.

The implemented methods will be synthesized in the following subsections.

5.2.1 Linear Scanning

The standard and easier way to do a search for an optimal solution is linearly go through all hypothesis while saving the best one. Since the final return is expected to be a heap, the saving results need to be extended to its size.

The key step of this method is selecting the discretization step that balances memory usage and time consumption. As expected this method raises problems for high redundancy systems as computational capacities are limited and considerations on memory usage need to be considered. Thus, when creating the hypothesis to test, a linear discretization method for each element of interest was implemented, bounding the number of hypothesis.

The ideal algorithm can be described as following (Algorithm 1).

Algorithm 1: Linear Scanning Algorithm

```
Inputs: PointsToOptimise, Model Data;
Outputs: Optimised Poses;

Hypothesis = Create_Testing_Hyphotesis();
Optimised Poses = Create_Poses_Structure();

foreach PointsToOptimise do
    foreach Hypothesis do
        EvaluteHypothesisCost(Hypothesis.Current, PointToOptimise.Current);
        Update_Optimised_Poses();
    end
end

return Optimised Poses;
```

5.2.2 Genetic Algorithms

This method can be defined as a search and optimization tool able to solve multi-constraint problems Deb (1999). Genetic algorithms recur to genes (variable of interest) to store a sequence or solution of interest. Most of common applications using this method start with two set of solutions and iteratively swap (exchange of genes between solutions) or mutate (random or methodical change of a given gene), creating a population of solutions. The algorithm can be described as following (Algorithm 2).

Algorithm 2: Genetic Algorithm

```
Inputs: PointsToOptimise, Model Data;
Outputs: Optimised Poses;

Population = Generate_Genes();
Optimised Poses = Create_Poses_Structure();

foreach PointsToOptimize do
    for NumberOfIterations do
        foreach Gene in Population do
            EvaluteHypothesisCost(Gene, PointToOptimize.Current);
            Update_Optimised_Poses();
        end
        Population = Generate_NewGenes(Population, mutationRate, swapRate);
    end
end

return Optimised Poses;
```

Within our proposed methodology we start with a higher number of randomly generated genes. Each gene is defined as a vector resulting of the external axis values. Then, each gene undergoes a reachability validation of the defined position. Iteratively new genes are generated throughout a fixed number of iterations and the optimized heap is built. The generation of each gene is based on the swap and mutation operations, that are randomly selected. In case of swap procedure, the second gene is also randomly chosen from the multi-gene population.

5.2.3 Simulated Annealing

Another optimization technique is the simulated annealing method, which is a probabilistic to find the global optima of a given function Kirkpatrick et al. (1983). This method starts from a random solution and iteratively searches its neighbourhood to define new possible solutions. Then, probabilistically decides to which solution it should iterate until untimely finds the global optimum.

However, when dealing with high redundancy system this method entails a high time and computation effort. Thus, a minor adjustment to the method was implemented in order to reduce the execution time of the method. A threshold was defined in order that the method runs iteratively until reaching a fixed number of solutions that verify such constraint, stopping without fully completing the algorithm, giving a secure and acceptable list of solutions while minimizing time consumption.

Another add-in was related to the initial point. Since this is neighbour-based, if the initial point and its neighbours do not produce a valid solution, the method would stop and a erroneous value would be found. As such, the initial point is randomly fixed within half robot's length to the goal point. The algorithm is shown next.

Algorithm 3: Simulated Annealing

```
Inputs: PointsToOptimise, Model Data;
Outputs: Optimised Poses;

Solution = Generate_Initial_AcceptablePosition();
Optimised Poses = Create_Poses_Structure();

foreach PointsToOptimise do
    while SolutionNumber < IntendedSolutionNumber do
        EvaluateSolution(Solution);
        Update_Optimised_Poses();
        Neighbours = Get_Solution_Neighbours();
        Solution = Select_Next_Solution(Neighbours);
    end
end

return Optimised Poses;
```

5.2.4 Potential Gradient

Similar to Simulated Annealing, Potential Gradient is an algorithm based on surrounding solutions of the current iteration. However, this algorithm stops at local optimums.

The iteration direction is defined by the sum of directional derivatives framed with the optimization function. Once determined what is the best directional vector a new solution is generated until reaching a local optimum.

Despite being computational light, this algorithm does not guarantee optimal solutions for any given problem.

5.2.5 Optimization Methodologies Comparison

Attempting to ensure a multi disciplinary validation process, two workcells with different properties were modelled and inserted in a custom simulator. Those workcells are displayed below in Figure 5.2.

Figure 5.2: At the left - a workcell with a cartesian external axis, a Fanuc IC30 and a cutting torch; at the right - a workcell with two kinematic chain, one composed by a rotative external axis (Ring) and a Motoman MH5 robot and the second by an external positioner.
[Optimization Trial Workcells]

A third cell was used, although it is not presented above. This cell has been physically implemented according to the national project CoopWeld.

The workcells here presented are focused in these redundancy systems composed by external axis, robot and operation tool. However the proposed approach is also applicable to simpler robotic cells.

In order to validate the methodology a set of cutting and welding jobs were generated using CAM software for the production of beams, MetroID BeamCut and BeamWeld, proprietary of SARKKIS robotics. These software generate a set of vectors containing poses that describe the given operation (see Figure 5.3)

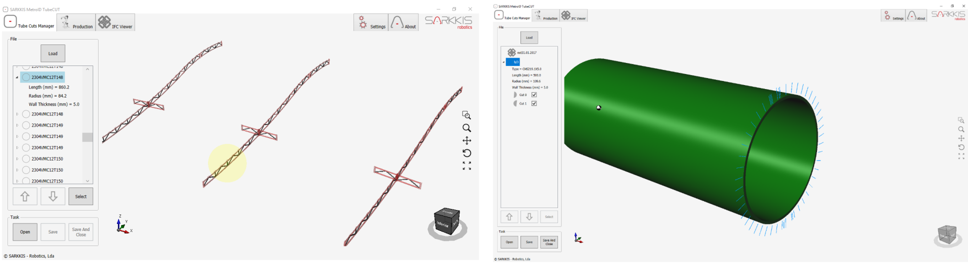


Figure 5.3: MetroID user interface.

Using these software it was then created several test beams. Examples are presented next in Figure 5.4. The idea behind the creation of those beams was to define different jobs that required external axis/positioners movement.

Figure 5.4: Beams Examples.

In order to evaluate each of the implemented algorithms there were considered three parameters: reachability percentage, time consumption and cost of reached solution. The results are summarized in table 6.1. These are according to a validation test of 15 beams, each with 5 to 130 operations, which resulted in a total of 563 points to be optimized. The results provided in the table are averages per operation of the correct achieved solutions.

Table 5.1: Results summary of the optimization methodologies comparison

Optimisation Methodology	Solution Reachability (%)	Time consumption (s)	Cost Value
Linear Scanning	100%	18.031	0.103
Genetic Algorithms	100%	1.022	0.098
Simulated Annealing	96.4%	0.740	0.147
Potential Fields	81.4%	0.412	0.134

These results were achieved once established the proper parameters for each algorithm. Those were determined by considering the best testing performance for random positions for each algorithm when considering memory management, time consumption and solution reachability.

Concerning Linear Scanning was implemented a discretization in 50 equally spaced hypothesis of each external axis/positioners based on their interval range. The Genetic Algorithm methodology was implemented using a cross rate of 50% and a mutation rate of 10%, for a random generated population of 1000, throughout 25 iterations. This was the set of parameters that produced the best results in an exhaustive study done with different parametrizations. We also limited Simulated Annealing reaching goal to a maximum cost of 0.15 in order to reach a higher number of solutions in a viable time frame. Moreover, Simulated Annealing was implemented using a multi dimensional neighbour radius of 8 increments. Each increment is considered to be the interval value of each external part when discretized into 1000 equally spaced hypothesis.

These parameters were validated accordingly to the results obtained from the cost function throughout the comparison trial. In order to determine the correct parameters for genetic algorithm and simulated annealing, a set of hypothesis were generated and the results are presented next in Figures 5.5 and 5.6.

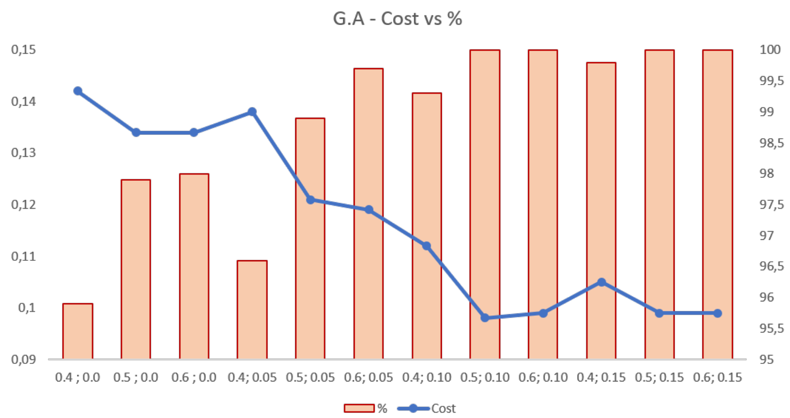


Figure 5.5: Genetic Algorithm Parameters Comparison

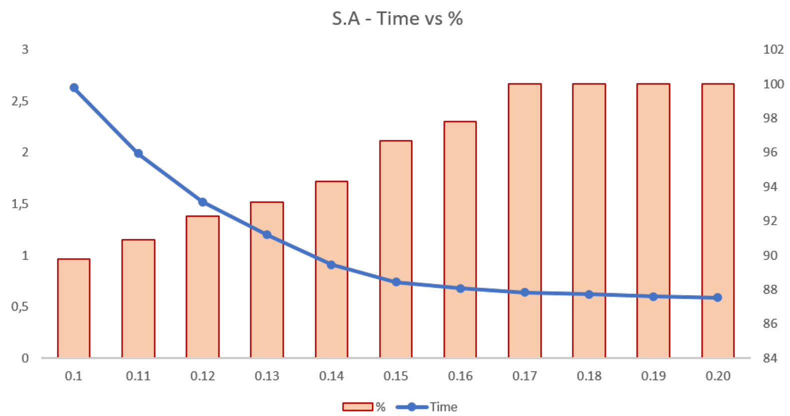


Figure 5.6: Simulated Annealing Parameters Comparison

5.2.6 Implemented Concept

Each of the proposed stages or layers are built using genetic-based algorithms as they proved to be faster and accurate. All these stages are related as the lower tiers are the optimization ground truth for the higher tiers, as portrayed in Figure 5.7.

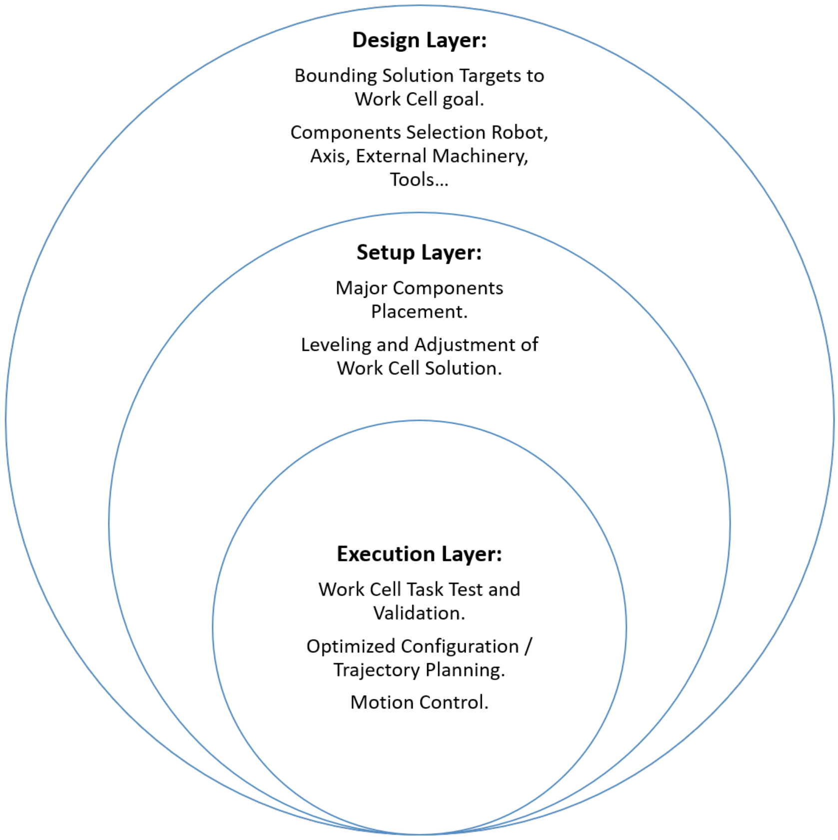


Figure 5.7: Cascade Multi Layer Diagram

The design stage promotes multi chromosome genes with equal dimension to the number of workcell components. Each hypothesis is coded through a digital key and the crossover and mutation commonly associated to this kind of algorithms is based on the modification of this key.

The setup stage ranges from a single chromosome to six chromosome genes that define the relative position of a component in the shop floor. The position follows an Euler nomenclature of a set of three Cartesian values (x,y,z) and a set of three orientation values (*roll*, *pitch*, *yaw*). This data is numerical, therefore the crossover and mutation of it is similar to typical genetic algorithms.

Finally, the execution stage intends to determine the best posture and configuration for the entire motion system within a workcell. Each body that inserts movement into the system is coded as a part of a multi dimension array that describes current joint positions. The crossover and mutation of sets of this array leads to the finding of the optimal pose for the system at each given point and time.

The classification of each layer is achieve by using a minimization of a cost function. For the design stage the objective is to achieve better workcell performance results. For the placement stage is to maximize the number of efficient operations concluded for a given workcell setup. And finally, for the execution stage the idea is to minimize system effort and maximize system reachability and efficiency.

5.3 Layers Overview

The following subsections intend to detailed present the features of each layer and how they are able to cooperate towards an optimal solution.

5.3.1 Execution Layer

The low level tier of the proposed optimization is related to strategy planning (motion planning) and validation of clean trajectories for a given workcell and task.

Depending on the complexity of the workcell a specific optimization algorithm can be followed based on a cost function to determine the optimal system configuration to reach a crucial operation point.

Commonly, a customizable genetic algorithm is used as this algorithm provides a better solution in a faster way. For each workcell a set of genomes (population) are created with N genes related to the number N of motion inserting components within the workcell. Each gene is responsible for the storage of the hypothetical value related to the component motion.

Then, by transforming the set through crossover and mutation inside the population a random range of hypothesis are tested, selecting the most suitable for each challenge.

Focusing on the specification for the optimization algorithm, it is important to recapture its key stages and features. The hypothesis are tested considering a seven features cost function that intended to minimize efforts and maximize the number of reached current and future poses.

Here, the importance of the Jacobian matrix is crucial. The Jacobian matrix is defined by the first derivative of the kinematics equations. Therefore the study of this matrix can provide useful information regarding singularities (as stated in the previous contribution) as well as linear and joint velocities and force responses.

Another issue that Industry 4.0 requires is related to usage of external positioners and conveyors. These elements insert some disturbance in the proposed concept as they function as free unlimited joints that interact with the system without being part of a traditional kinematic chain.

Despite that, the usage of these components is common in industry mainly for repositioning, transportation and handling operations. Therefore, a solution is presented within our proposal. Each component is considered to be a separate kinematic chain that interacts with specific parts of interest, such as a conveyor to move a part or a flipper system to rotate a beam.

These systems only affect the attached objects and their interference on the optimizer is only considered under cases those objects are part of the optimizer goal. In those cases a "software reset" to the component is applied and the relevant motion of it is relative to its current position.

Essentially the presented solution is scalable to cope with these changes while the test parameters remain the same.

A new contribution that can be added to the solution finding is the time reduction of the planning operation as applying a genetic algorithm to solve kinematic challenges proves to be faster than numerical and exploratory methods.

On top of this optimization algorithm a probabilistic algorithm is used as this computes a faster solution while ensuring a complete path.

5.3.2 Setup Layer

A recurrent challenge in all industrial workcells is the placement of components to ensure a clean global layout while validating each component functionality and contribution for the workcell efficiency. This a double stage process as first, from a macro standpoint, the relative layout is selected and then, secondly, the position, orientation and leveling of each component are set to complete the intended tasks.

Currently, in industrial environment this is accomplish by a well trained operator that based on experience and shop floor constraints design the layout and workcell assembly features.

The proposed approach intends to use intelligent and flexible decision making to this selection. Thus, at this layer, the components are already selected and a new genetic algorithm is used. Here, the concept of genes differ from the previous layer. Each gene now may possess more than one chromosome. This set of chromosomes defines the features that are intended to be optimized for the correct placement of components.

This varies from one chromosome scenarios (such as finding the height of a stand or a robot platform) to several chromosomes that can describe cartesian position (x, y, z), orientation (*roll*, *pitch*, *yaw*) or even just relative leveling of components.

Once created the test dataset it is required the usage of a validation protocol. In that regard, each operation intended to run in the workcell should be tested. In order to do that it is required to simulate the workcell full execution: trajectory planning, motion and system control.

Our approach uses the execution layer explained previously and consequently its cost function while adding constraints to avoid components overlapping. This can be described by a sum of two terms (Equation 5.2).

$$w_1 * ExecutionCost + w_2 * CollisionValidation \tag{5.2}$$

The *ExecutionCost* term of the previous equation is defined by a set of complex sums of multiple tasks to be validated. Considering welding workcells this would be a set of N beam/tubes/profiles with a defined number M of welds that are require to be produced within the workcell. Thus, this term can be defined by equation 5.3.

$$\sum(Execution_{op_{1,1}}, ..., Execution_{op_{N,M}}) \tag{5.3}$$

The term $Execution_{op}$ can be defined as the return value of the Execution Layer affected by another important consideration to be had here regarding the evaluation of operation failure. This is included in the classification automatically as for unreachable targets the cost function of the Execution Layer return a significant high value.

The *CollisionValidation* term is simply a two value function to describe the proposed placement as a collision free solution (*CollisionValidation* = 0) or not (*CollisionValidation* = 1). Then the weights w_1 and w_2 are merely a tool to reject solutions on which *CollisionValidation* = 1, since that $w_2 >> w_1$. This way a maximum limit threshold is reached in colliding cases, and therefore, they are discarded.

5.3.3 Design Layer

The ultimate higher tier layer of the proposed approach is related to full workcell design and specification. This is accomplished by using a set of constraint and a components database with possible robots, axis, external positioners, tool, among others.

Currently the developed algorithm receives as input the operation type, parts to be handled, distance of operation, number of robots, usage of external axis/positioners and placement interval for the parts to be handled, while outputting a set of classified possible partial (in cases where there is no possible solution for all challenges) or total solutions.

Once again, to do so, it is used a genetic algorithm. To compute this layer each gene is composed by a list of robots of equal size to the number of robots selected, an external axis chain and a set of positioners if applicable and a tool suitable to complete the operation type (welding torches for welding, cutting torches for cutting, grippers for picking operations...). Upon gathering this information a virtual workcell is created.

Then, our proposed approach is to use a cascade software to integrate this hypothetical virtual workcell and validate it by using the Setup and Execution Layers. Thus, the value of each hypothesis may be defined by the optimal output of the Setup Stage. This allows to completely define an entire workstation based on a couple of constraints.

5.4 Chapter Summary

Throughout this chapter, it was presented a multi-layer solution to be applied to all robotic installations. This solution allows one to avoid the common pitfalls associated with robotic poses configuration and overall workcell design. A genetic-based methodology was applied in order to comply with industrial requirements of optimal manufacturing execution and design. This methodology comprises three stages with similar importance to the steps of workcell construction, implementation and control. All these stages share a common ideology of hypothesis testing and classification through a process of crossover and mutation of a starting population. This population is achieved by applying constraints and randomly generate a set of viable initial hypothesis for a specific problem. The proposed approach is flexible enough to be applied in multiple cases and for a wide range of workcell operations, robot specification and surrounding components.

Part III

Proposal Validation

Chapter 6

Solution Validation

The validation process is separated in two sections. The first one intended to test the usage of the advertised methodology on a custom simulated scenario.

To ensure the validation of all stages, a scientific scenario was selected composed by an external circular ring, a robot platform moving along the ring, a robot and a random attached tool on top of the platform and a fix table. The simulated workcell is displayed in Figure 6.1.

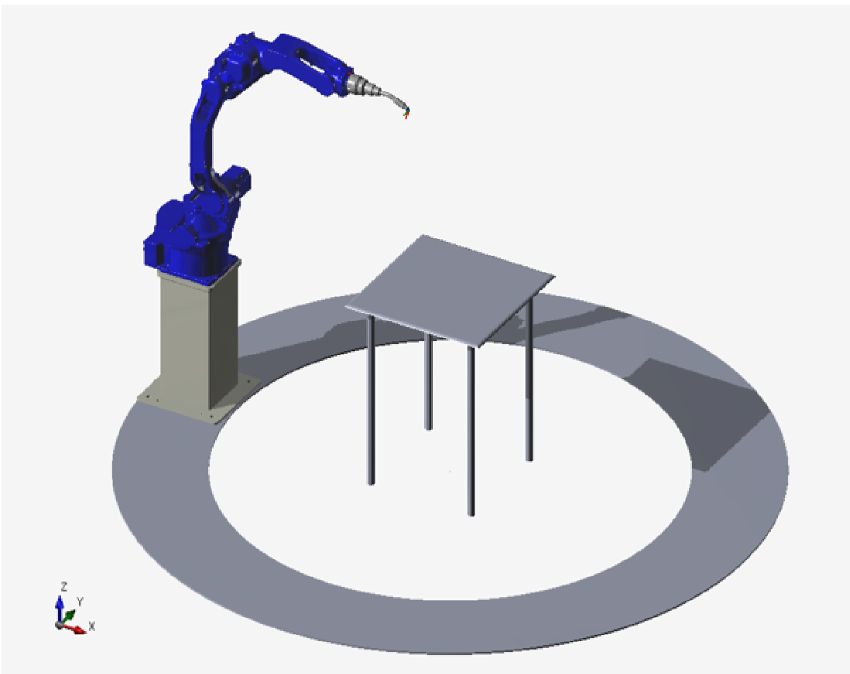


Figure 6.1: Validation testing scenario

The circular ring is a simplistic representation of an external axis, with an inside diameter of 1500mm and an outside diameter of 2500mm. The robot platform is a simple stand with a square base and a total height of 700mm. The selected robot was a Motoman MA1440 and the attached tool is an ABICOR W500 welding torch. At last, the fix table has a total height of 1000mm while its top is a square with a side length of 800mm. The ring and the table are centered with the origin of the simulated environment.

The experimental validation was conducted using the simulation framework presented before in Section 4.1 that allowed to generate virtual workcells and test the full extent of the proposed approach.

Then, the proposed approach was inserted in four industrial scenarios presented next: Coop-Weld, CLARiSSA, ScalABLE 4.0 and Digital Factory. All these workcells share the concept of Industry 4.0 and manufacturing automation. The concepts were tested and validated using proprietary SARKKIS software for the generation of goals and operations to be concluded.

The optimization concept varies from one workcell to another based on shop floor constraints and workcell production. This set of real industrial applications requirements ranged from automation of previously existing machinery to workcell design and component selection.

The opportunity to collaborate with SARKKIS allowed to apply the developed approach in more industrial facilities with excellent results. However, due to commercial interests, these cases can not be displayed.

The following sections will describe the contribution of the proposed methodology in both simulated environment and in the mentioned industrial scenarios.

6.1 Simulated Validation

This section will present three custom tests regarding each of the layers presented in Chapter 5. The goal is to validate the usage of a genetic-based solution for process optimization.

6.1.1 Execution Layer

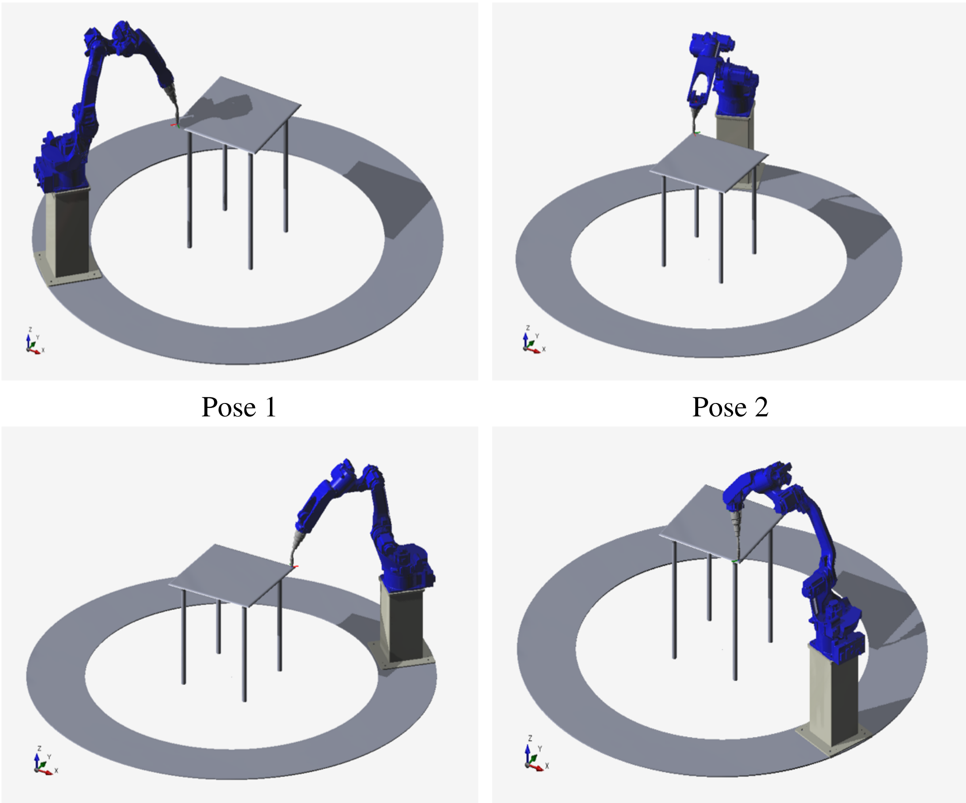
The results associated to this section were already discussed in greater detail previously. However to link the testing scenario to the execution of the proposed solution, the genetic algorithm associated to this stage was put to test.

Four clear poses were defined, each pose defines one of the corners of the table. Another relevant data is the starting point. For each pose the starting point was defined by a zero value array that visually results in the posture seen in Figure 6.1.

The tested poses are defined using an Euler nomenclature (x, y, z, w, p, r), being x the value along the x-axis present in previous mentioned figure, y the value along the y-axis and z the value along the z-axis. Furthermore w, p, r are defined the orientation of the end-effector at the end goal following the *roll-pitch-yaw* (*r-p-w*) convention.

Finally, each solution is given concerning only the joints that insert motion, and, thus, in this case is a set of seven values, one allied to the value of the circular track, and six related to the value of each robot joint for the given pose and this order.

The solutions are displayed graphically in Figure 6.2.



Pose 1 Pose 2

Pose 3 Pose 4

Figure 6.2: Execution Layer graphical visualization

These cartesian representation of each pose can be found next, following a table with the top results for each one:

- Pose 1: Right back corner (-375, -375, 1000, 0, 0, -135) - Table 6.1.
- Pose 2: Left back corner (-375, 375, 1000, 0, 0, -45) - Table 6.8.
- Pose 3: Left top corner (375, 375, 1000, 0, 0, 45) - Table 6.3
- Pose 4: Right top corner (375, -375, 1000, 0, 0, 135) - Table 6.4

Table 6.1: Top results for Pose 1

Index	Joint Array	Cost
1	[45.1, 0.1, -8.4, -36.7, -0.2, -22.8, 0.3]	0.068
2	[44.8, -0.2, -8.4, -36.7, 0.4, -22.8, -0.8]	0.069
3	[45.5, 0.4, -8.5, -36.7, -0.8, -22.8, 1.5]	0.071

Table 6.2: Top results for Pose 2

Index	Joint Array	Cost
1	[-69.1, -8.1, -35.3, 0.0, -12.0, -73.9, 153.0]	0.282
2	[-20.8, 8.2, -35.4, 0.0, 12.1, -73.9, -152.9]	0.282
3	[-69.5, -8.3, -35.4, 0.2, -12.2, -73.9, 152.7]	0.283

Table 6.3: Top results for Pose 3

Index	Joint Array	Cost
1	[-135.0, 0.0, -8.4, -36.7, -0.1, -22.8, 0.1]	0.068
2	[-135.3, -0.3, -8.5, -36.7, 0.6, -22.8, -1.1]	0.070
3	[-134.6, 0.3, -8.5, -36.7, -0.7, -22.8, 1.3]	0.070

Table 6.4: Top results for Pose 4

Index	Joint Array	Cost
1	[159.3, 8.2, -35.4, 0.1, 12.1, -73.9, -152.8]	0.282
2	[158.9, 8.1, -35.3, -0.1, 11.9, -73.9, -153.2]	0.282
3	[111.0, -8.1, -35.3, -0.1, -12.0, -73.9, 153.1]	0.283

6.1.2 Setup Layer

To evaluate this tier of the proposed approach, the stand of the robot was deleted from the scene and an assumption of a pending robot was made in order to determine what should be the optimal position for the robot concerning its height relative to the floor.

Thus, this was a one-chromosome problem (the height of the robot). The genetic algorithm solutions were bounded from 0mm (imposed by the floor) and 1500mm. The initial population was 100 with a crossover percentage of 50% and a mutation rate of 10% The testing positions remain the same as the previous subsection (the four corners of the table).

In Table 6.5, the top three results for the height consideration are presented. The cost value on the table are the result of Equation 5.2. Figure 6.3 displays the graphical outcome for the robot configuration at each corner.

Table 6.5: Top results Robot Height selection

Index	Robot Height	Cost
1	807mm	0.452
2	802mm	0.452
3	813mm	0.453

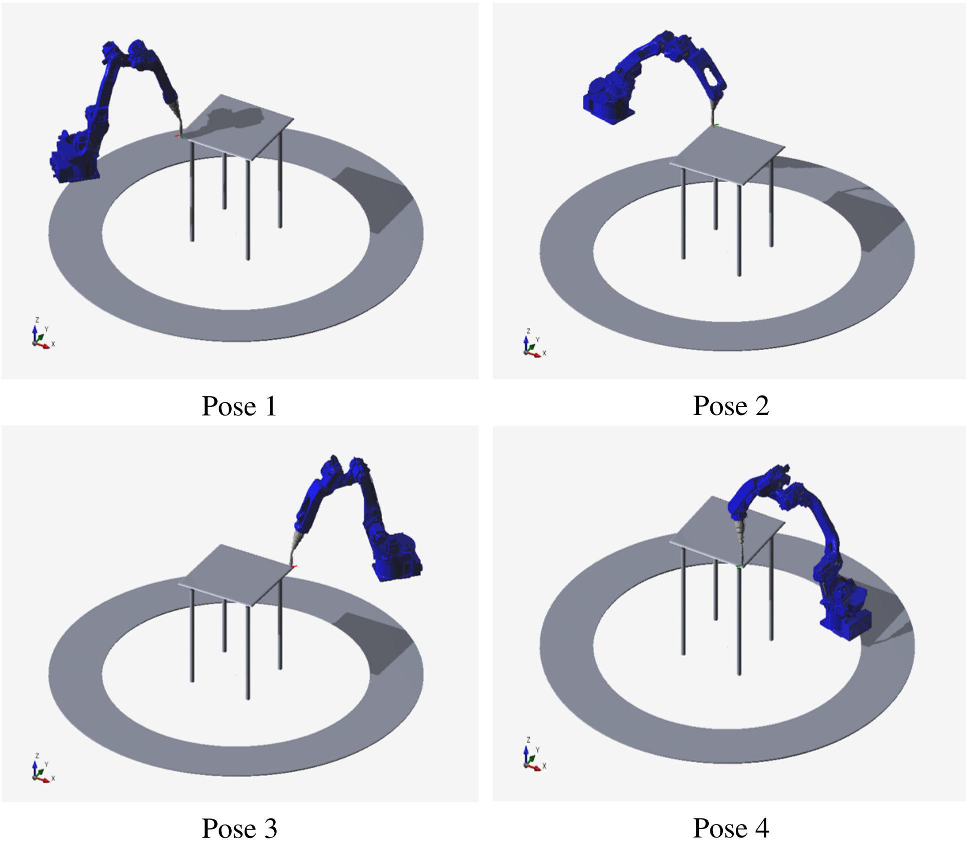


Figure 6.3: Setup Layer graphical visualization

6.1.3 Design Layer

The workcell used for testing and validation and presented in Figure 6.1 had all main components and its relations selected. In order to validate the proposed design algorithm the focus of this layer was to identify the ideal robot to use in the system while fixing the remaining components: circular track, torch, robot platform and table. On that regard there were three initial options:

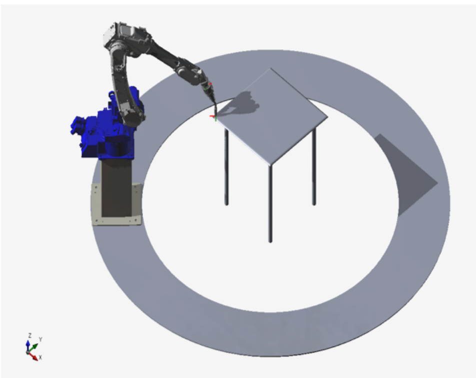
1. Motoman MA1440.
2. Panasonic TL1800.
3. Comau Six.

The test conditions (poses) remained the same. In Table 6.6, the classification results for each robot for the design challenge are presented.

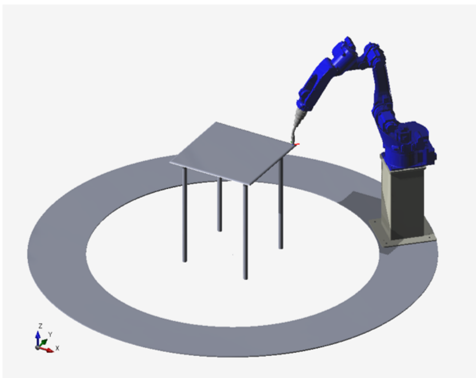
Table 6.6: Classification for the Different Robot Hypothesis

Index	Robot Tested	Cost
1	Panasonic TL1800	0.674
2	Motoman MA1440	0.700
3	Comau Six	0.983

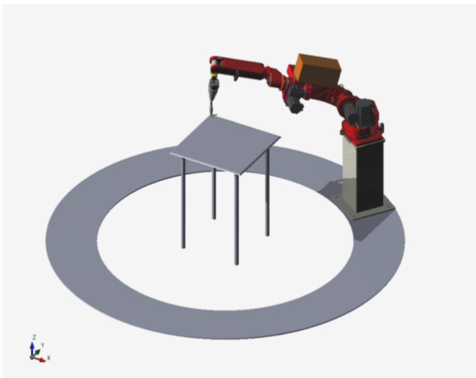
Throughout the analysis process all robots were able to provide solutions. Nevertheless, the motoman MA1440 and the Panasonic TL1800 achieved the more comfortable postures to the overall system as stated in Figure 6.4.



Panasonic TL1800



Motoman MA1440



Comau Six

Figure 6.4: Comparison of robots' posture

6.1.4 Simulation Validation Summary

The three layer solution here presented (execution, setup and design) allow the user to incorporate a modular solution into the design and control of a manufacturing workcell.

In this simulation validation section, a scientific approach is explored to point the usage of the algorithm in all three process stages.

First, the optimization of the system posture and configuration to optimally reach a pose intends to reduce the time and joints effort of the system moving components and outcomes a set of goal values to be reached in order to complete a task.

Then, a tier related to component positioning is presented and tested using a recurrent problem in robotic workcell architecture design: the robot positioning in the cell.

At last, the more complex part of this solution incorporates all the above and automatically designs the workcell following some constraints. Here we selected a set of possible robots giving the algorithm the freedom to decide the most suitable solution for the underline problem.

All these solutions are genetic based algorithms and prove to be a fast and secure ideology for optimization methodology.

6.2 Industrial Validation

The industrial validation is based on the four industrial scenarios presented before. Despite its applicability in real industrial environment, once again due to external restraints some examples are still presented using the developed simulator. Each indiviual subsection presented next focus one of these projects.

6.2.1 CoopWeld

CoopWeld is a collaborative cell that incorporates assisted assembly with a camera/laser projector duo and automatic welding of beams, assisted with pneumatics flippers for the beam rotation. The chosen robot is a Motoman MA1440 positioned with a 90º pitch on a structure inserted in the sole external axis of the cell, a 14m track from Yaskawa (Figure 6.5).

Figure 6.5: CoopWeld Workcell

The main goal of this project is to promote the collaboration between human and robotic operators. The concept of collaborative system in present due to the insertion of the hand-guiding of the overall motion system (axis and robot) and a projection mapping interface.

CoopWeld intends to automatically generate robotic instructions for assisted assembly and automated welding of beams. The main challenges is this workcell were to decide the relative position of the robot facing the remaining components and, upon the workcell implementation, the control of system motion through the optimization of poses.

The optimization algorithm for enhancement design was applied to the robot's height and position in relation to the axis of the track, as well to the position of the flippers and stands that support the beams and the usage of different torches configurations. The algorithm was applied envisioning the industrial requirements imposed related to the robot's reach that comply with the specified set of beam between a standard 600HEA beam and a 200HEA beam.

Here, the genetic algorithm provides an important contribution as it is designed to validate multiple solution sets and classify their proneness for a defined task using a configuration planner.

The following sub-section will detailed show the achieved results to comply with the already mentioned challenge.

6.2.1.1 Optimization Approach

To assess the multi-variable problem behind the CoopWeld workcell implementation it is required to define a two layer testing group. The first layer is related to components analysis, while the second is related to component placement. In that regard the possible solution can be defined by a set of solutions (see Figure 6.6 for a reference example).

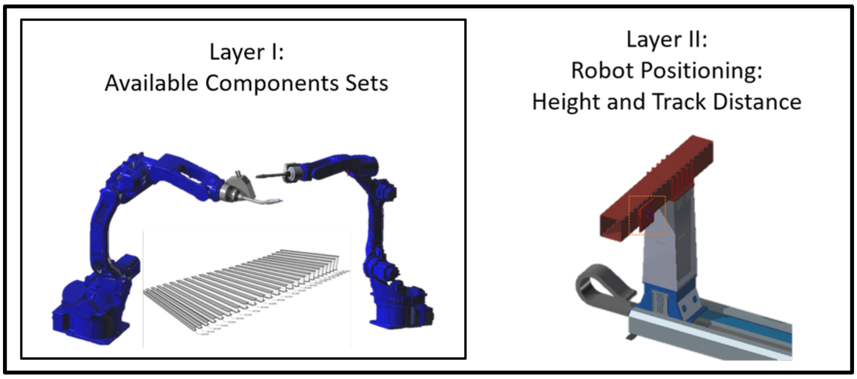


Figure 6.6: CoopWeld Hypothesis Set

Each hypothesis is composed by the robot, one of the welding torches and a beam.

Upon built a hypothesis based solution, the optimization algorithm for pose definitions is applied to every move gathered from the main software, BeamWeld from SARKKIS Robotics. The optimization algorithm for pose definitions can be approached in two phases. The first phase is to calculate the easiest configuration for a given pose, this includes the positioning of the robot's joints as well as any selected external axis, in this use case it will only be the Yaskawa track.

This analysis allows the cell to operate in the most comfortable configuration at any given time, thus eliminating the risk of a sudden change of the configuration in the production of continuous operations such as scanning and welding. Then, a collision checker is ran to validate the resulting configuration of the entire system.

The second phase of the optimization algorithm for pose definitions is the path planning to the validated configuration retrieved from the previous phase. With the two phases the cell is capable of executing scans and welds with a considerable rotation of the tools without the worry of collisions or irrational movements along the procedure as depicted in Figure 6.7.

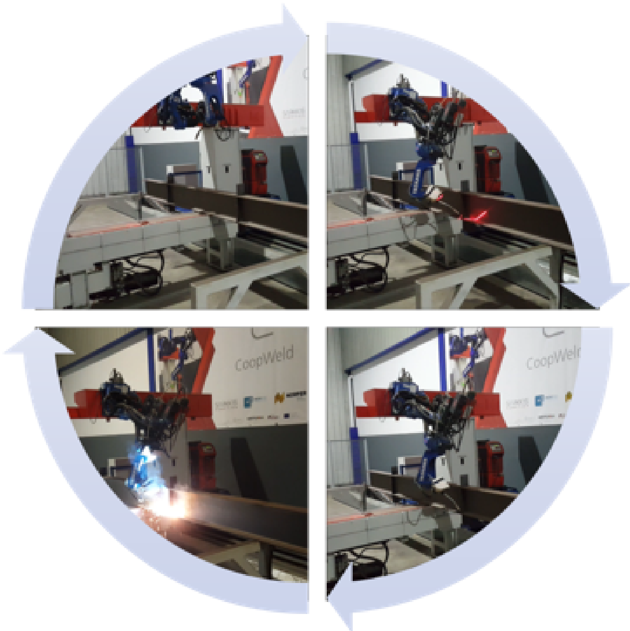


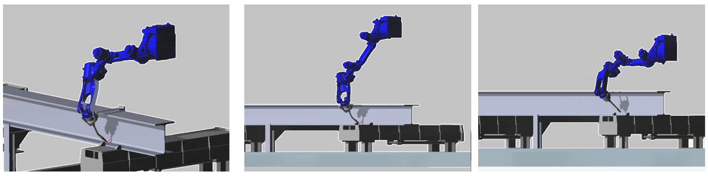
Figure 6.7: CoopWeld Operation Sequence

The optimization methodology requires as inputs the workcell components to be tested but also the bounded limits to compute a final solution. In that regard a distance to track from the robot placement was bounded by the interval of 0.5m to 1.5m along the y-axis (distance to the track), and by the interval of 1.5m to 2.5m along the z-axis (height to the ground).

By the process of randomly generating workcell composition, the classification is based on the genetic approached mentioned. Under the constraints imposed to the system, a starting population of 1000 random solutions is continuously modified storing the best suitable set of hypothesis until reaching the total of 100 iterations.

Based on the already mentioned parameters of interest, a set of possible outcome positions and components were returned for the previously mentioned elements, leading to the selection of such elements and, consequently, allowing the development of the correct scale and height of the structure that wields the robot, a key element of the whole cell.

The algorithm analyzed around 200 possible welds on more than 20 beams. Some hypothesis are shown as an example in Figure 6.8. The associated cost are stated in Table 6.7.



H1 H2 H3

Figure 6.8: Solution graphical visualization

Table 6.7: Cost results for H1, H2, H3

Hypothesis	Torch	(Y, Z) mm Position	Cost
H1	Round	(-959, 1926)	0.186
H2	Round	(-959, 2426)	0.311
H3	Straight	(-1002, 1626)	0.278

The optimal result led to the implementation today present in the industrial facility, being selected the round torch and positioning the robot at (-959, 1926) mm.

6.2.2 CLARiSSA

CLARiSSA stands for Cooperative Dual-Arm Robot for Structural Steel Fabrication and it's a European Robotics initiative aiming to develop an innovative cooperative robot for welding operations in assembly tasks for structural steel fabrication. The system is assembled with a dual-arm of Comau Six Robots attached to a rotation plate that's ceiling mounted to a large structure installed on a 12m track (Figure 6.9).

Figure 6.9: CLARiSSA workcell

The main goal of this project is to handle the assembly and welding of beams, delegating one set of operations to each arm of the robotic system. While one arm is responsible for picking parts and place them correctly on top of the beam the other is responsible for the tack and welding operations.

The workcell interacts with a human operator through a designed user interface application that allows the user to obtain feedback on the workcell state and select projects to be completed.

This way the schedulling of workcell tasks becomes user controlled while the optimization and completion of such tasks is based on autonomous robotic processes.

The underline challenge in this project is related to the coordination of motion of multiple robotic arms and design of specific beam holding components to ensure the maximization of tasks.

At the time of the integration the project was largely developed so the optimization algorithm for enhancement design was only applied to the position and height of the stands assigned for the securing of the beams for production. Identically to the CoopWeld project, a set of possible positions and features were returned for a better efficiency of movements.

Due to the nature of the system build it's not possible to control the robot and all the external axis in a coordinated manner, since that they are controlled by two different control units. Therefore, the pose optimization returns a single value for the track position and the angle for the rotation plate at any given operation, optimizing the configuration of the robot without any movement of the external axis. All poses are validated trough a collision checker and then the path planner describes the route to the valid destination allowing invasive welding configuration evading all elements, as is shown in Figure 6.10.

Figure 6.10: Invasive Welding Configuration

6.2.3 ScalABLE 4.0

ScalABLE 4.0 is an on-going European project[1] that intends to lead to the development of an open scalable production system framework (OSPS) that enables optimization and maintenance

[1] https://www.scalable40.eu/

of production lines.

The proposed methodology was applied here to optimize the construction of a mobile robotic solution for multi operation adaptability.

From a design standpoint the main goal is to define the proper components (robot and gripper) to use in order to complete the projects' use cases requirements. This stage is iterative and its completion provides both components to use and its placements for the raw robotic structure.

At this point, the methodology was applied in the Simoldes' use case. The simplistic overview of the real scenario is a conveyor belt where the parts to be handled travel and the mobile platform mentioned before (as display in Figure 6.11).

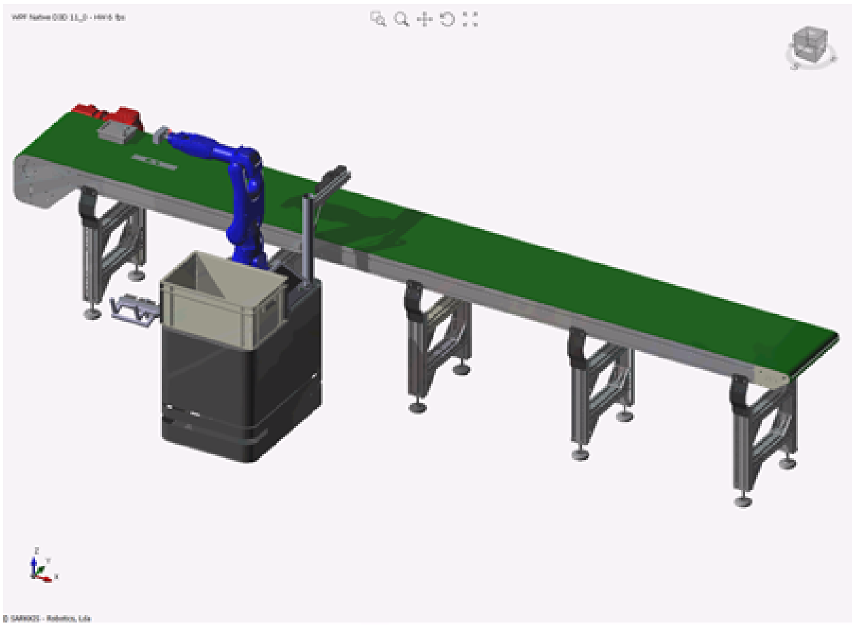


Figure 6.11: Simulated ScalABLE 4.0 Simoldes' initial prototype

For each operation an extra optimization procedure may be required to define container or part positioning on top of the built mobile platform. Facing a set of objects to handle, and the operations related to the handling, a gene with two chromosomes was created based on robot and gripper to be tested.

From the list of previously selected robots, the one that minimized the cost function throughout the validation procedure and ensured higher application scalability was the Motoman HC10.

Regarding gripper selection, none achieved a full completion of every proposed task, therefore the number of selected grippers was increased to achieve that goal. Thus, a multi-gripper solution was selected, using a gripper switching station.

At last the robot planning tier of the proposed methodology in this case is rather simple, as the assembly of the workcell reduces the number of collision interaction to be considered. Nevertheless the optimization algorithm is still applied to created smooth trajectories and motion orders.

6.2.4 Digital Factory

Digital Factory is a projected robotic cell for the manufacture of the pipe lines for industrial sprinkler. The whole cell consists in two robots MA1440 from Motoman each mounted in a separated stand, a track of 7m with a mounted turn, another fixed turn mounted in a stand to produce the secondary tubes to provide the divergencies in the main tube and a part warehouse to supply the production.

The main purpose for optimization usage in this project is related to placing of components over the workcell layout. The choice of components was previously set. Another important methodology application is related to the control of the robotic workstation through the complete range of operations: grasp, pick, place, cut, tack and welding.

The spatial constraints in this project are the most demanding ones as the given free shop floor space precluded most non-overlapping configurations.

Every single of the previous mentioned elements were inserted in the optimization algorithm for enhancement design envisioning the best possible combination of height, rotation and distance for a smooth and effortless transition between work stations, thus returning the optimal workcell layout.

The optimization algorithm for pose definitions is applied in all the operations of the process, this include the pick and place the of the divergencies of the pipe line in the respective place, the opening of the section for the insertion of the divergency and the weld of the inserted divergency. In the initiation of the weld operation the algorithm must process the configurations of both robots in the same work area without leading to any collisions, since one of the robots is placing the divergency in the newly cut opening and the other must weld it secure before proceeding to the full weld.

Another key contribution of the optimized planner is related to the removal of the completed tube. When concluded the process the tube will be filled by divergencies and, thus, to avoid collision at each point of extraction the interpolated motion of the attached system track plus turn require the generation of a collision-free optimized path to reduce time consumption of the operation while ensuring its safe completion.

To comply with both industrial and safety requirements there is also a synchronization control unit that manages robot operation with external machinery operation. This way it is possible to have multiple projects and tasks simultaneously.

The result of the optimization design methodology is explained in greater detail next.

6.2.4.1 Component Optimal Positioning Placement

The Digital Factory workcell design can be considered a complex challenge. Most components required optimal placement considerations while the full system should comply with all operations inherent to the workcell.

Even though most components were already selected, most placements were unknown. The fixed parts of the workcell were the input and output warehouse, the input feeder, the robotic track with coupled turn and the fixed support. Two reference planes were defined based on these components. A central plane across the center of the track and a reference plane coincident with the track exterior surface. All the remaining components should be placed on a restricted area given by the relative distance to the defining planes.

Therefore initially a set of constraints should be collected in order to provide the need input for the optimization methodology. These constrains are presented in Table 6.8.

Table 6.8: Constraints for Digital Factory workcell Design

Component	Constraint Description
Robot1	Robot Height relative to the floor (Z); Robot distance to central plane bounded from 0.5m to 1.5m (y). Robot distance to reference plane bounded from -1.0m to 1.0m (X). Robot Base Orientation (R).
Robot2	Robot Height relative to the floor (Z); Robot distance to central plane bounded from 0.5m to 1.5m (y). Robot distance to reference plane bounded from -1.0m to 1.0m (X). Robot Base Orientation (R).
Part Warehouse	Warehouse distance to central plane bounded from 1.5m to 2.5m (y). Warehouse distance to reference plane bounded from -1.0m to 1.0m (X). Warehouse orientation was fixed.
Fixed Turn	Fixed Turn distance to central plane bounded from 0.5m to 1.5m (y). Warehouse distance to reference plane bounded from -1.0m to 0m (X). Fixed Turn Orientation (R).

The generic application of the algorithm produced results considering several scenarios while assuring the execution of the task as depicted in Figures 6.12 and 6.13.

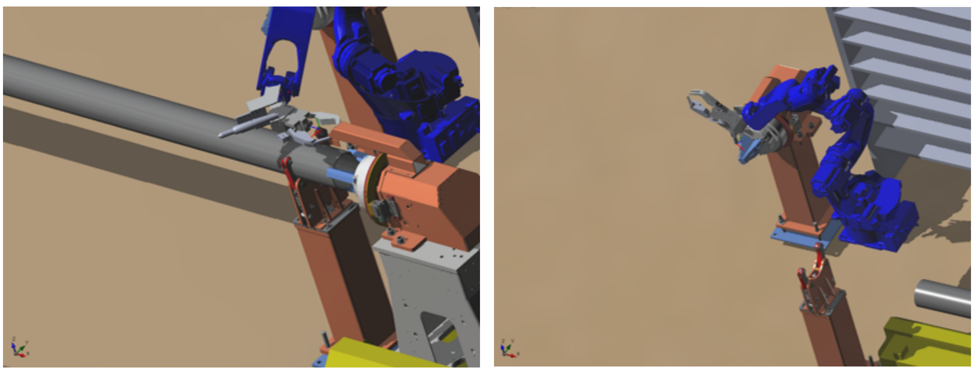


Figure 6.12: Digital Factory Operation Testing - 1/2

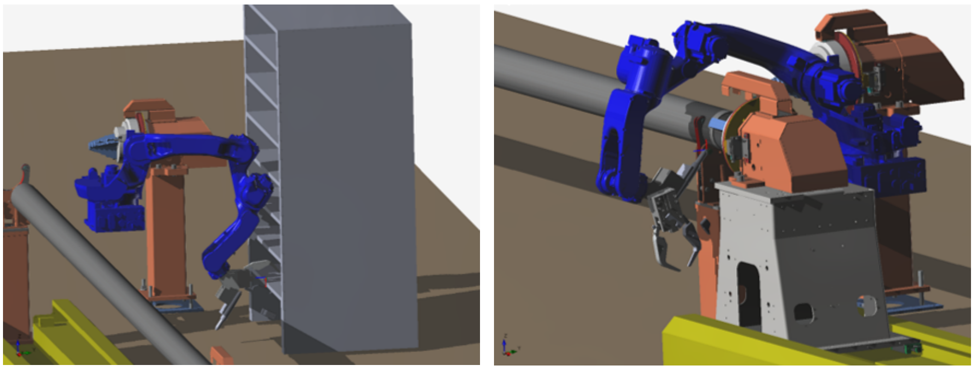


Figure 6.13: Digital Factory Operation Testing - 2/2

Each operation retrieved a partial cost. The sum of each operation for a hypothetical workcell layout provided the cost for the solution. Initially the population of the genetic algorithm was composed by 1000 sets of genes with 13 chromosomes. These genes were composed by:

Generic Chromosome = [$R_{1,x}$, $R_{1,y}$, $R_{1,z}$, $R_{1,r}$, $R_{2,x}$, $R_{2,y}$, $R_{2,z}$, $R_{2,r}$, W_x, W_y, FT_x, FT_y, FT_r]

Each of the initial genes is randomly generated based on the bounding constraints and from that point on, through crossover and mutation of genes, new hypothesis are tested. The rate for crossover was set to 50% and the rate for mutation was set to 15%.

This optimization returned the optimal relative position for the components, achieving a similar result to Figure 6.14.

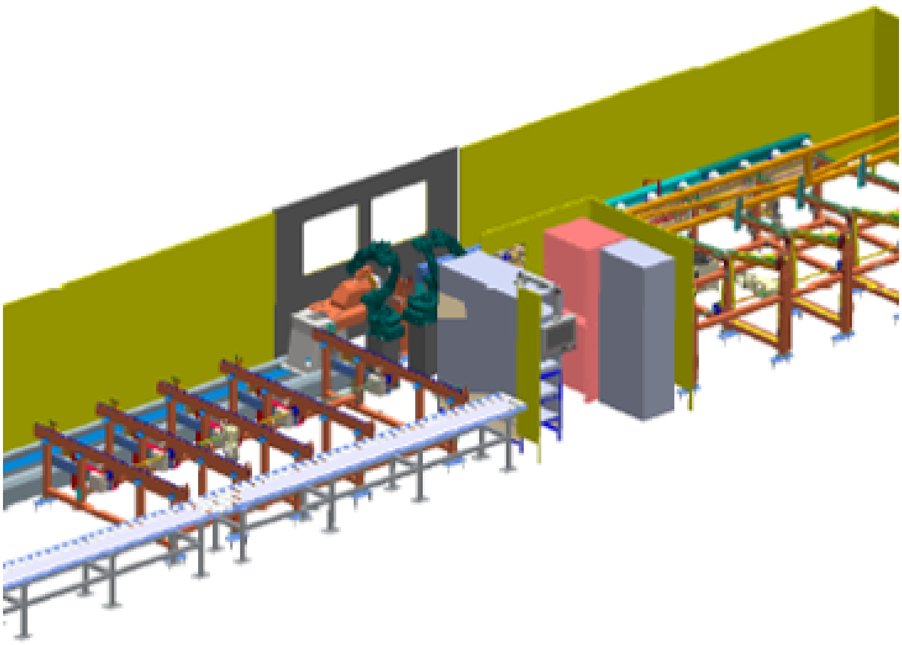


Figure 6.14: Digital Factory's 3D Representation

Despite having the optimal results an additional constraint was added at the end of the process to minimize the manufacturing effort of the auxiliary components. This constraint was fixing the same height for both robots and redefine the remaining components around them. The final results are displayed in Figure 6.15.

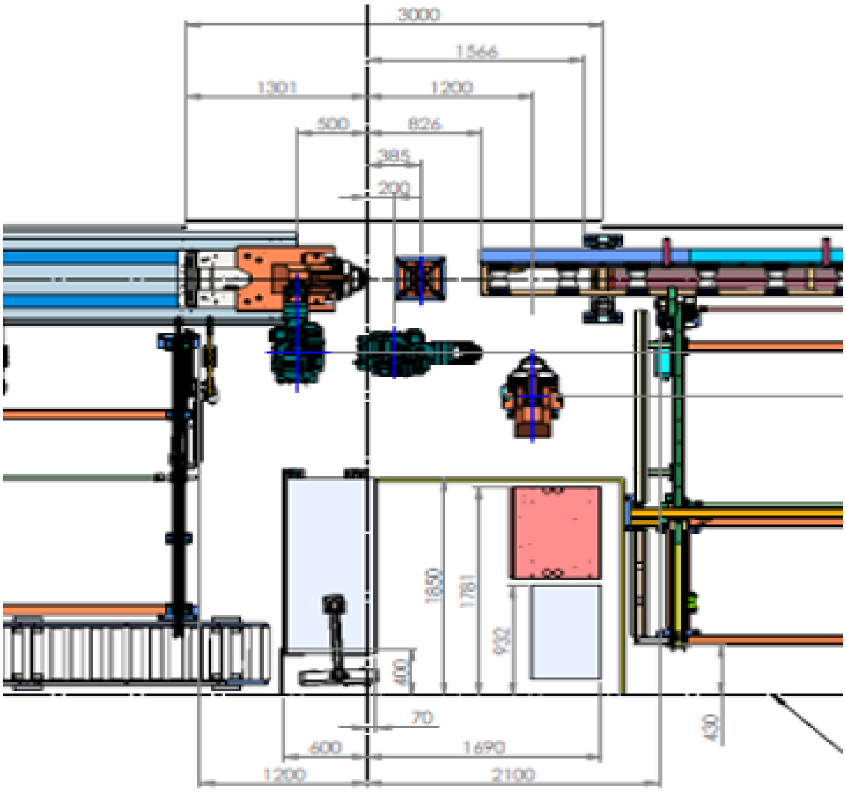


Figure 6.15: Digital Factory's Layout

6.3 Chapter Summary

Throughout this chapter a variety of validation tests were presented. First, a simplistic workcell was defined in order to validated each stage of the proposed methodology. Then, four real cases were presented, each with a particular improvement provided by the proposed solution.

Chapter 7

Conclusions and Future Work

Over the past few years, the exponential industrial competitiveness growth has fueled the rapid development of automation and machinery control. In this new industrial Era, robotic systems are good solutions for various manufacturing procedures.

The development of hardware for robotic systems has played a critical role to date, but the need for software frameworks development has clearly been identified and its role in robotics is becoming increasingly recognized in recent times.

During the course of this thesis project, a simulator has been developed and implemented. This simulator allows to generate virtual workcells for a wide range of robots, as well as, to create custom workcells to manipulate and validate robotic operations in a controlled environment before their deployment into the real world. Furthermore, this simulator is equipped with a set of communication and planning packages that allow the preview of future work agendas, as well as, the update of a real industrial workcell by following the concept of the digital twin.

Another important software in today's industrial production lines is the CAM software. To this regard, some improvements were developed and tested using the SARKKIS' vector generation software using sections of the proposed work. This software is quite important as it bridges the project development steps with the shop floor production steps through a well structured vertical information flow.

The simulation software and the CAM improved software are the framework base for this thesis project, as they provide enough information to identify robotic operations that when correctly processed may generated both simulation or robot controller programs.

In this thesis project, a multi-tier solution was developed to optimally deal with some of the most common challenges and complications in the design of robotic cells. A genetic-based methodology was applied in order to comply with industrial requirements of optimal manufacturing execution and design. This methodology comprises three stages with similar importance to the steps of the workcell construction, implementation and control.

The three layer solution presented in this thesis (execution, setup and design) allows the user to incorporate a modular solution into the design and control of a manufacturing workcell. A scientific approach is described whereby it is possible to use a genetic algorithm in all three process stages.

First, the optimization of the system posture to optimally reach a pose intends to reduce the time and joints effort of the system by moving components so that a set of goal values can be output to reach task completion. Then, the tier responsible for component positioning is presented and tested while addressing a recurrent problem in robotic workcell architecture design. Finally, the more complex part of this solution incorporates all the above and automatically designs the workcell following some constraints. Here we identified the correct robot to use in an scientific test case.

All these stages are genetic based algorithms, which have proved to be a fast and safe method for robotic optimization strategies. They share a common ideology of hypothesis testing and classification through a process of crossover and mutation of a starting population. This population is achieved by applying constraints and randomly generate a set of viable initial hypothesis for a specific problem.

The concept of robotic optimization and its utility in robotic workcells' design gains traction when this kind of algorithm is applied. Importantly, future tasks to be completed by the robot will be smoothly completed and the reachability issues will be eliminated. Thus, the application of this methodology can provide robotic system integrators and generic industrial end-users a design tool to comply with a wide range of operations, fixtures, constraints and components.

Furthermore, the proposed validation has been applied to simulated and industrial scenarios.

Using the already mentioned simulator, a simplistic representation of a robotic kinematic chain and an object of interest is generated. From this generated environment and providing the system the correct inputs it is possible to identify the importance of poses optimization, robot placement of even component (in the presented case, the robot) choice.

The validation of this methodology is also achieved using four industrial application examples. All three stages and their possible interaction become relevant in industrial scenarios as each of them require the integration between layers or the application of a specific one.

In CoopWeld, a set of robot positions was considered to ensure task completion and scalability. The results proved to be effective in both simulated and, more importantly, real industrial environment as the projected workcell is continuously producing nowadays.

In CLARiSSA, the influence was greatly diminished due to previous workcell and component selection. Therefore the optimizing design methodology mainly allowed to validate and extend the project task list compatible with the workcell.

In Scalable 4.0, a high level tier of optimization was applied, achieving most suitable robot for the underline task and correct gripper tool to complete the predefined challenges.

In Digital Factory, an higher level of requirements was inserted into the proposed solution, and the result provided a complete description of workcell layout. The projected workcell is already implemented in industrial environment and despite spatial constraints and a reduced area of work, the sequence of operations inherent to the cell construction was smoothly accomplished.

Overall the main benefits of the proposed methodology are related to gains in precision and efficiency, as well as, reduction of the limitative constraints.

Industrial data collected from the industrial systems currently operating with the solution developed in this thesis project show some relevant information on improvement of task completion. The minimization of risk and maximization of comfortable robotic work area at each step allows to fully complete a task without requiring external modifications.

The time consumption of each module of this solution is variable to the complexity of a given workcell. Nevertheless, and even though the solution was designed for offline programming, the application of this solution can be considered also for online problems and can be considered a large improvement over the traditional human-experience "method" that is currently the go to in every workcell design and control.

At the execution stage optimization, the time consumption is significantly lower compared with the time the path planner takes to compute a solution and it is around 25 ms to 50 ms. The setup stage is bounded by the number of components to place, however it is expected to always be limited to a maximum of 1 s per component. At last, the design stage is the most time consuming one, as naturally multiple components require computation and the generation of virtual models is highly damaging for the overall time. However, even this stage achieves completion under 5 minutes.

The proposed methodology is an added value solution that can be applied to multiple workcells with different identities. It is therefore generic and can be considered an universal solution in robotics.

7.1 Future Work

The future of robotics is unknown, but it is foreseeable its use in industry will only expand over time, as technological developments are continuously been explored and the optimization in robotics is a fairly new topic.

Future development of the new methodology developed here would include the implementation of more constraints to consider process and workcell constraints, such as on-arm fixtures management (cables) and machine safety. Furthermore, it would be interesting to apply the three stages as a complete cascade solution for a desired un-designed solution in an empty layout.

Others robotic areas may also be subject of future work as the problem of automatic calibration or automatic grasping definition can be solved with a well specified problem within this methodology.

Another important bottleneck currently found on implemented workcells is related to the adaptation of robotic software to different levels of requirement. Simpler workcells should prompt different optimization techniques than more complex workcells.

In a near future, it would be interesting to consider further intelligence insertion on this solution. The insertion of machine learning and automatic adaptation to requirement level may provide faster solutions or even better solutions. Genetic algorithms have proved to be a great ground truth, nevertheless for specific use cases, simpler methods such as Linear Scanning can be more effective.

In short, the proposed solution can be classified as a great ground truth, nevertheless the balance between optimization strategies should be consider in future iterations.

7.2 Final Remarks

The proposed solution proves to be a standard modular possibility for the robotic area. In conclusion, the proposed approached is flexible enough to be applied in multiple cases and for a wide range of workcell operations, robot specification and surrounding components.

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Appendix A

Appendix

A.1 Collaborative Welding System using BIM for Robotic Reprogramming and Spatial Augmented Reality

P. Tavares, C. Costa, L. Rocha, P. Malaca, P. Costa, A.P. Moreira, A. Sousa, G. Veiga. *Collaborative Welding System using BIM for Robotic Reprogramming and Spatial Augmented Reality*. 2019. Automation in Construction. An International Research Journal, Elsevier, IF: 4.0

Collaborative Welding System using BIM for Robotic Reprogramming and Spatial Augmented Reality

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Abstract

The optimization of the information flow from the initial design and through the several production stages plays a critical role in ensuring product quality while also reducing the manufacturing costs. As such, in this article we present a cooperative welding cell for structural steel fabrication that is capable of leveraging the Building Information Modeling (BIM) standards to automatically orchestrate the necessary tasks to be allocated to a human operator and a welding robot moving on a linear track. We propose a spatial augmented reality system that projects alignment information into the environment for helping the operator tack weld the beam attachments that will be later on seam welded by the industrial robot. This way we ensure maximum flexibility during the beam assembly stage while also improving the overall productivity and product quality since the operator no longer needs to rely on error prone measurement procedures and he receives his tasks through an immersive interface, relieving him from the burden of analyzing complex manufacturing design specifications. Moreover, no expert robotics knowledge is required to operate our welding cell because all the necessary information is extracted from the Industry Foundation Classes (IFC), namely the CAD models and welding sections, allowing our 3D beam perception systems to correct placement errors or beam bending, which coupled with our motion planning and welding pose optimization system ensures that the robot performs its tasks without collisions and as efficiently as possible while maximizing the welding quality.

Keywords: Robotic Welding, BIM, Spatial Augmented Reality, Structural Steel Construction Industry

1. Introduction

The increasing competitiveness drives the Architecture, Engineering, Construction (AEC) industry to push automated data transfer among design and production stages. In that regard, it is possible to identify key areas that still require standardization and flexibility in order to match the industrial requirements with the development of software and management available to be used in the shop floor of manufacturing industries.

Over the last few years, we have been noticing a clear effort towards improving such conditions while assuring the interoperability between all key processes and partners required to perform a given task. These efforts lead to the creation of an ISO standard for data modeling - the Industry Foundation Classes (IFC) developed by buildingSMART [1]. Up until recently, the IFC based work flows are more commonly seen in the design phase of the building projects, being less available for the fabricators. Despite being a data modeling strategy not completely exploited yet, it shows some interesting characteristics as it allows the creation of an automated information flow between design and production. Furthermore, the IFC can describe the complete design and production process in a unique file, simplifying the integration between teams and companies.

Another result reached by this effort is related to the insertion of automated solutions for solving problems concerning harsh, dangerous and high precision tasks. In particular, robotic solutions excel in reaching these requirements. As such, lately it is possible to clearly identify a tendency for the usage of these solutions [2, 3]. The goal is to work towards the development of robots that are able to autonomously adapt to several applications and environments. For this to happen robots must become highly efficient operators, able to complete highly demanding tasks and to cooperate with both external machinery and human operators. All these conditions arise in importance when considering the current organizational growth. Currently such growth is associated with the development of small and medium enterprises (SMEs) [4]. Facing this, well structured data models as well as flexible and easily adaptable robotic solution can improve many industrial fields, in particular the steel construction industry regarding the cutting and welding tasks.

Considering the specific use cases of the steel fabricators domain, over the years, the evolution in design methodologies and

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tools has lead to the usage of computer assisted methods (CAD and CAM). Commonly the result of these systems will guide to the planning and execution of a proposed task.

However, the previous standards, such as DSTV files, were struggling to fulfill the goals, preventing the steel constructing industry from achieving the so desired efficient flow of information, between the design and specification phases and the production stages. Due to these limitations, the steel fabrication sector required the development of a new format with higher acceptance. In that regard, an extension to the IFC standard was considered by major corporations as possibility to close the gap previously identified and fulfill the industrial requirements [5].

Currently, the steel fabrication industry is also demanding the automation of several inherent production processes, as a way to shorten the project's life cycles and reduce the related costs. Several applications can be found actively working in industrial shop floors. These solutions vary from automatic robotic cells for welding and surface treatment and automatic handling [6]. Such advanced robotic systems become effective as a standalone partner in construction.

In this paper we discuss the introduction of this new file format and the main advantages that it can bring to the industrial process, focusing not only on the information flow in the fabrication process, but also in the amount of information that IFC can transfer and how this information contributes for process automation. Furthermore, an efficient automated robotic welding solution will be presented considering several key modules that contribute to the information flow from design specifications to robotic execution, namely Spatial Augmented Reality (SAR) for helping the operator tack weld structures, 3D beam perception for improving robotic seam welding operations along with planning of the robots movements trajectories and task optimization.

The paper is organized as follows. Section 2 presents a brief overview on the current state of development of robotic applications. Section 3 introduces the overall system architecture and provides a description of the key features of the collaborative robotic welding cell. Section 4 presents some experimental results for showing the full integration of the main modules described in previous sections. Finally, Section 5 highlights the overall conclusions and discusses challenges for tackling in the future.

2. Related Work

The steel fabrication industry has been using file formats with limited information to manage the production cycle. These limitations have great impact in how the information flows at the shop floor level, increasing the probability of human error and affecting the quality of the products produced by the company.

The Building Information Modeling (BIM) term was first introduce in 1992 [7] and refers to a building design methodology characterized by the generation and use of coordinated and internally consistent computable information about a building project in design and construction.

Despite of the high added value related to the standardization of information throughout all stages of the steel fabrication process, a correct definition of such standard is still debatable. Over the years, the DSTV file was the main file format used in the production process, but the limitations in both geometrical descriptions and additional information to vertically connect design and production stages, raises the need for a more complete file format.

The Industry Foundation Classes (IFC) data model is a file format specification that intends to unite both ends of the process and facilitate interoperability in the architecture, engineering and construction (AEC) industry. The IFC model specification is open, available and registered by ISO as an official International Standard ISO 16739:2013. It is an object-based file format with a data model developed by buildingSMART (formerly the International Alliance for Interoperability, IAI) and is a commonly used collaboration format in Building Information Modeling (BIM) based projects [8].

Lately, the usage of robotic solutions in industrial scenarios has also raised in importance. These kind of solutions ensure process efficiency in a wide range of industrial applications, namely in harsh conditions and for automating repetitive tasks. However, there are some pitfalls concerning their usage in dynamic work cells or complex tasks. In that regards, some efforts have been made in order to provide a more complete and robust approach to these concerns. The usage of sensing systems arise in importance as they allow to generate a correct virtual model describing the industrial environment conditions. One of the main focus of the robotic community is towards building the world model from the perception system. Multiple application have been implemented and validated using laser technology such as laser-dot or laser-line which provides the correct set of detailed information to described parts for object recognition and position detection [9].

Recently, there has been additional efforts regarding human machine interfaces and collaboration between human operators and robotic systems. An official International Standard ISO/TS 15066:2016 [10] has been defined in order to accommodate this ever growing interest of having both robotic systems and human operators working towards the completion of a task. In this domain, SAR systems [11] have been emerging as an intuitive and reliable approach to transmit information to the operator for helping him perform his tasks faster and with less mistakes. By accurately projecting alignment information directly into the environment [12] the operator no longer needs to use error prone and time consuming measuring tools. Moreover, this information can be complemented with wearable devices such as Head Mounted Displays (HMDs) [13, 14, 15], smart watches [16, 17] and hand-held displays [18] for not being restricted by the environment surfaces that act as projection canvas. Besides welding applications, SAR systems using projection mapping techniques have been expanding to other industries, namely in assembly and maintenance tasks in the automotive sector [19] and also in painting shops in aeronautic factories [20].

Robotic applications currently lack in flexibility to autonomously adapt to dynamic constraints that can be found in industrial scenarios. Steel fabrication industries have made efforts towards modularity, flexibility and efficiency improvement of automated robotic solutions mainly in cutting and welding operations [21, 22]. Although all the presented works have been validated by the scientific community, they have some limitations when applied on industrial use cases. An integrated solution that uses a complete information flow allied to a flexible human-robot collaboration can be very valuable as it enhances the efficiency of both manual (human) and automated (robot) processes, resulting in a increase in the overall productivity.

3. System Architecture

For improving the flexibility and ensuring the long term maintenance of a system, it must follow a modular and scalable architecture for allowing its evolution over time for dealing well with a range of similar tasks. Considering these core characteristics and focusing on a welding robotic system, it is crucial to take into account three major areas, such as, information acquisition and processing, work cell sensing along with system control and adaptation. These can be arranged within the diagram shown in Figure 1 and will be described in the next sections.

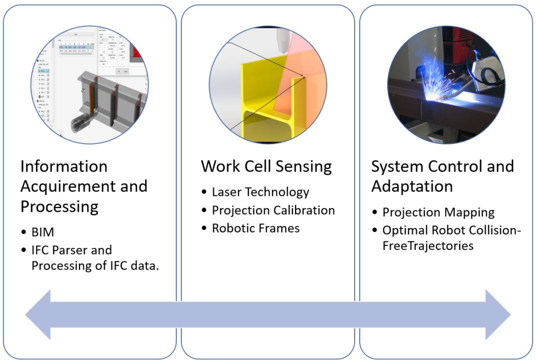

Figure 1: Architectural breakdown of the design and production.

The main stages of the proposed work cell are summarized in Figure 2. It presents how the information extracted from BIM files is used for implementing a collaborative welding cell that includes a human machine interaction system using spatial augmented reality for speeding up the assembly of the beam attachments along with 3D sensing systems for improving the welding quality and a collision free path planner for ensuring safe operation of the welding robot.

3.1. IFC creation

Throughout this project, the Tekla software was used for handling CAD and BIM information. Tekla Structures (TS) is the building information modelling software (3D detailing) that has been the reference source of BIM information from which *.ifc format files are obtained and used for production. It was chosen due to its widespread usage in the construction industry (specially steel construction).

The steps to obtain, from TS, the ifc file for a given structure / assembly are fairly straight forward and use Tekla's own

Figure 2: Overview of main processing stages of the CoopWeld cell

IFC export system. Nevertheless some small steps need to be in place prior to export so that all important information is obtained. These sequence are done by activating Tekla's functions in order to properly export a set of crucial welding parameters.

The output is be a IFC file containing all relevant information for the project execution that then is made available for production. Once again, this is a specific approach to Tekla Structures IFC export procedure, known at the moment, expecting that similar BIM modelling applications will generate similar data output.

3.2. IFC Parser

Parsing IFC files is not an easy task to accomplish given its complexity and flexibility. The buildingSMART [1] organization provides all the tools and information required to do it, but the complex definition of the elements, the hierarchy and the relation of each other inside the file make this a complex task.

Currently there is an extensive offer of alternatives, free or commercial parsers like the OpenBIM [23] or some of the toolboxes of parsers that can be found on buildingSMART website or IFCWiki [24] for example. This can be a boost for the integration process but will not be enough for software development, requiring some knowledge of the IFC hierarchy to know were you can find in the file the properties that you need for the software development.

3.3. IFC Information Processing

Once the IFC data is parsed and transformed into usable information, it is given to the MetroID BeamWeld software (developed by SARKKIS - Robotics) for generating vectors of interest for performing a IFC defined weld operation. The automatic parsing and transformation of IFC data into usable information for programming a welding robot is a huge improvement in the fabrication process, not only for offline programming but also for the traceability of the process (dimensions, materials used, finishes) due to no longer being necessary to be manually done by an operator.

Looking into to the MetroID BeamWeld software, the weld information can dramatically speed up the preparation of the welding operations, since it is no longer necessary to manually detect the joints to be welded within the Computer Aided Design (CAD) models. Using the IFC CAD data and weld specification it is possible to automatically generate the welding vectors shown in Figure 3. For achieving this, advanced algorithms were developed for detecting the joint line and ensure collision avoidance between the welding torch and the parts to be welded.

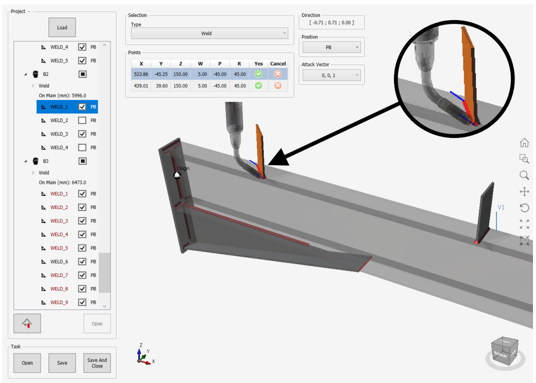

Figure 3: MetroID BeamWeld Software

3.4. Spatial Augmented Reality Human-Machine Interface

Spatial Augmented Reality (SAR) systems using projection mapping techniques can provide immersive Human-Machine Interfaces (HMIs) for helping human operators perform their tasks faster, more accurately and with less mistakes. They have a wide range of applications in the manufacturing industry and when integrated with Building Information Modeling (BIM) systems they can be used for providing contextual information directly into the environment location where it is needed. For our particular use cases, the SAR system that we developed projects into a structural beam the place in which the operator should place and tack weld the metal parts (that will be later on seam welded by a robot). This immersive approach of transmitting the design specifications to the operator allows him to perform the assembly tasks faster and without relying on error prone procedures (such as measuring tapes, ruler squares or protractors). Moreover, given that the information is provided on demand, our system transfers the burden of constantly checking the design schematics from the operator to an automated system, which results in an overall improvement of productivity while reducing possible mistakes when interpreting the manufacturing design specifications.

For achieving a projection accuracy within the manufacturing tolerances required by most welding factories (bellow 3 mm of error), the SAR system must be properly calibrated and it must also be able to detect where are the physical objects that will be used as a surface for projecting information. Moreover, the projected data must be clearly visible even in highly illuminated factories. With these requirements in mind, we chose laser galvanometer scanners [25] as our projection hardware (in particular, the MediaLas ILP 622) and developed the calibration tools, beam perception software and vector rendering pipeline for achieving a reliable and accurate SAR system for welding applications.

3.4.1. Hardware Layout

In our particular welding cell, the robotic arm is moving on a linear track and is attached to a tower for improving its reachability when welding on the top section of the beam. As such, for avoiding a dedicated support for the galvanometer scanner, we attached it on the opposite side of the robotic arm (as seen in Figure 4) and at the minimum distance from the beam that would allow to project on our intended work area, which currently are beams with at most IPN 500[1] dimensions that have a cross section of 500 mm in width and 185 mm in height.

By attaching the projector to a movable robot it makes the whole projection system more compact and more cost effective, since a single galvanometer scanner is enough for projecting marking information in our welding cell (which can handle beams with up to 12 meters in length). If we had chosen to attach several static projectors to the ceiling it would result in a more expensive and less accurate SAR system and it might also have occlusion problems due to the robot and its moving tower.

The hardware layout shown in Figure 6 maximizes the precision of our SAR system because it uses the full field of view of the galvanometer scanner, allowing to place the projector as close as possible to the objects in which it will be projecting information (beam). This layout also makes SAR system more tolerant to slight errors in calibration (that introduce projection displacements that are linearly magnified as the projector becomes farther away from its projection surface). For example, assuming a vertically projected line on top of a horizontal plane, we can use trigonometry to find the spatial displacement on the horizontal plane that will occur when a rotation error is introduced by the overall calibration of the projection system (which includes the intrinsic and extrinsic calibration of the projector and camera along with the detection of where is the beam in relation to the projector). Namely, Equation (1) allows to conclude that at 1 m, a 0.1 degrees of rotation error will introduce

[1] `https://www.cad-steel.eu/steel-sections/ipn-european-standard-beams`

a 1.75 mm of projection displacement while at 3 m the error would have increased 3 times to 5.25 mm.

$$HorizontalDisplacement = Tangent(Rotation) \times ProjectorHeight \quad (1)$$

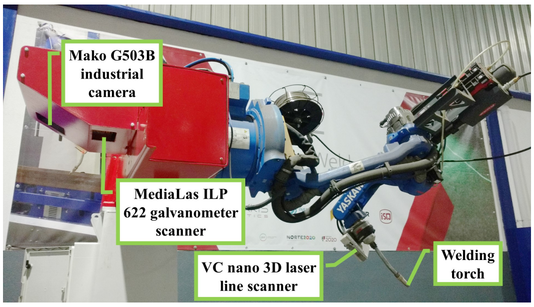

Figure 4: SAR hardware (left) mounted on the moving track tower alongside the welding robot (right)

For performing laser triangulation using lines projected by the galvanometer scanner we also attached a 5 MP Mako G503B grayscale industrial camera with a 12 mm lens. We place it with a X and Y base line distance of around 150 mm for ensuring that we could generate accurate 3D measurements in our sensing volume (hardware layout shown in Figures 5 and 6). The large baseline distance between the camera and projector is due to the extensive work area in which we need to perform measurements. Namely, the perception of beams with up to IPN 500 dimensions at a distance from the camera of around 1200 mm when they are in a H position and around 900 mm when they are positioned in a I configuration. Moreover, this large baseline was split into two axis components for ensuring that the vertical and horizontal projected light planes (used for detecting where is the beam in relation to the projector) did not came close to the camera optical axis (since this would cause severe loss of triangulation precision).

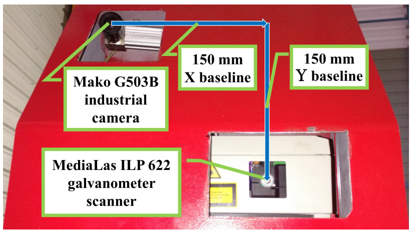

Figure 5: Relative disposition between the camera (top left) and the galvanometer scanner (bottom right)

3.4.2. Hardware Calibration and Beam Perception

Projection mapping systems are able to seamlessly integrate into the environment and provide immersive interfaces because the information is shown directly on top of the surfaces in which

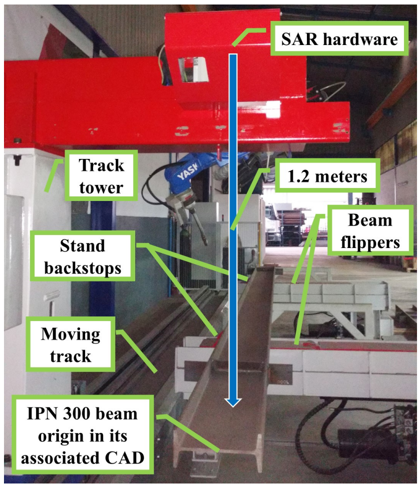

Figure 6: Overview of the SAR hardware (galvanometer scanner and camera at the top of the image) mounted on a moving track and its projection target below (IPN 300 beam, laying on top of two beam flipping platforms)

it is needed without requiring the operator to wear any extra devices. For achieving this level of accuracy the sensing and projection hardware must be properly calibrated [26, 27] and the workspace must be virtualized and maintained in a consistent state with the physical world.

For performing the 3D virtualization of the welding cell we used the Eyeshot CAD rendering engine[2] and for ensuring proper simulation of the projector within the 3D environment we modeled the galvanometer scanner as a virtual pinhole camera [28] (which will be used for generating the 2D vector images required for projecting the HMI information).

For configuring the virtual pinhole camera model, we developed a calibration system for estimating the intrinsic and extrinsic parameters of both the projector and its attached camera. Moreover, we also developed a system for performing visual inspection of the calibration and perception modules for ensuring it is ready for production (example in Figure 8).

For ensuring consistency between the virtual and physical world, we implemented a 3D beam perception module for updating the pose of the simulated camera within the Eyeshot virtual workspace. Our capability of using the galvanometer scanner hardware for both HMI projection and laser triangulation is critical for being able to estimate the beam position in relation to the projector with high precision (which is a requirement for proper projection mapping).

Given that the beam is placed on top of a rotating stand and is touching its 2 alignment backstops (shown on the left side of the beam in Figure 6), our perception system only needs to correct for operator placement errors (along the track direction) and also beam bending problems. For dealing with the first

[2] https://www.devdept.com

issue we project a line along the beam longitudinal axis and estimate where is the start of the beam in relation to the projector and the moving track start position (this way we are able to accurately project information even if the camera is not seeing the beam start since we can rely on the high accuracy track encoder to update the projector position when the track moves). For computing the necessary corrections for dealing with the second problem we project two lines across the beam and estimate each line 3D centroid (on the beam top face) for computing the beam direction and also its height in relation to the projector (example of the projection lines on top of a IPN 300 beam in a I configuration shown in Figure 7). We rely on the beam center (origin of the CAD coordinate system shown in Figure 6) as a common reference frame between the virtual and physical beams because its width and height may vary a few millimeters due to manufacturing problems. As such, for our welding use cases, aligning the virtual and physical beams centers for evenly distributing the manufacturing error on both sides of the beam seems to be the best approach to deal with these issues.

Since our welding cell can operate on beams with up to 12 m in length, we needed to rely on the tower linear track encoder for estimating how much did the projector move in relation to the beam beginning. As such, when a new beam is placed within the welding cell or it is rotated by the stand, we move the tower to the beam beginning and correct its displacement in relation to the projector. Then we can trust on the high accuracy linear track encoder to update the projector pose as long as the beam is not moved. On the other hand, since the beam bending might be irregular, when the tower moves to a new welding position we perform a local calibration (using the approach that relies on the two transversal lines discussed earlier) in which we update the virtual camera pose for mitigating the beam bending issues.

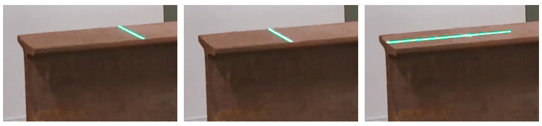

Figure 7: Projection of two transversal lines (left and center) for estimating the beam direction and distance in relation to the projector and also a longitudinal line (right) for computing the beam start position along the moving track

3.4.3. Generation of HMI Information from IFC

The Industry Foundation Classes (IFC) is a neutral and open file format that can be used for exchanging BIM specifications between designers and constructors. It provides in a single file the CAD data and the meta-information (such as their spatial disposition and welding sections) required to produce structural steel assemblies. Within our particular welding cell configuration we start by loading the main structural beam from the IFC file and then incrementally add the HMI information and CAD models of the parts that must be welded later on (such as plates on the beam flange, web or end sections for attaching the beam to other structures or reinforce its connections). Our HMI system provides two different and complementary ways for conveying to the operator the assembly and welding information that was extracted from the IFC file. The first is through a large tactile monitor in which the fully assembled parts are shown in several 3D views along with instructions and controls for the operations that are required (examples presented in Figures 9 and 11). The second interface relies on the SAR system for projecting alignment shapes directly into the beam surface for helping the operator place and tack weld the beam attachment structures (examples shown in Figures 10 and 12). This alignment information is automatically generated by computing the intersection lines between the CAD models of the beam and its attachments followed by a post-processing stage for simplifying and optimizing the lines for reducing projection flickering.

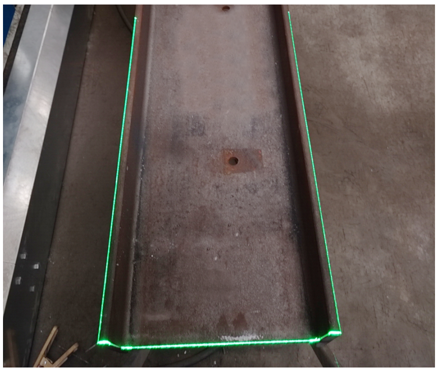

Figure 8: Projection of the beam outline (in green) for performing a visual inspection of the SAR hardware calibration and the beam perception modules

For validating and also evaluate the accuracy of the proposed approaches for calibrating the SAR hardware and generate its information from BIM, we performed several tests in which marking information was projected for informing the operator where he should place beam attachments (example in Figure 12). Our experimental evaluation showed that the SAR system was able to achieve a projection error below 3 mm, making it suitable for the proposed welding applications and our end users.

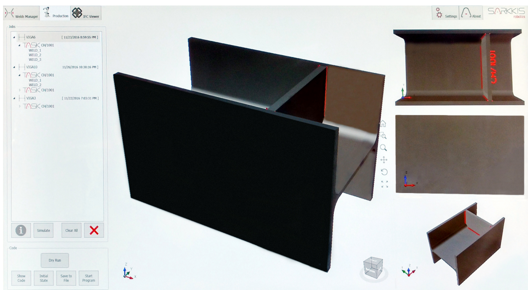

Figure 9: Tactile user interface for a small demonstration beam

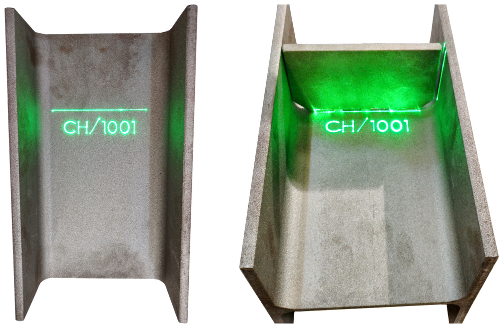

Figure 10: Projection of alignment information for the placement of the beam attachment shown in Figure 9

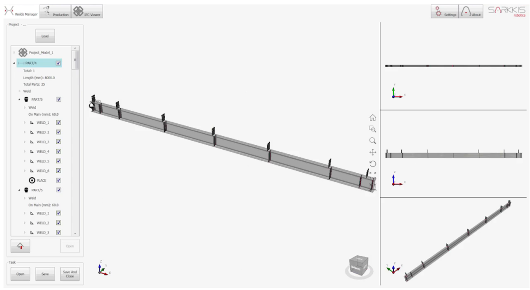

Figure 11: Tactile user interface for the production of a structural beam

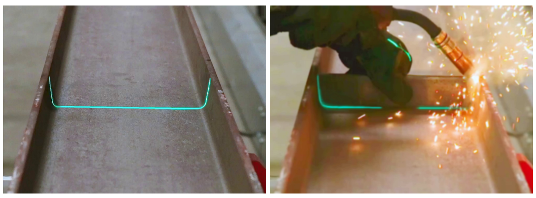

Figure 12: Projection of alignment information for one of the beam attachments shown in Figure 11

3.5. High Precision Laser Based Localization System for Robotic Welding

The placement phase of the metal structure in the robot's workstation is usually performed manually using an industrial crane due to the weight of the structure. However, given its inherent inaccurate placement, it does not meet the positioning requirements for the welding operations to be performed automatically by an industrial robot.

In the CoopWeld robotic cell (shown in in Figures 6 and 20) the number of degrees of freedom in which the beam can be moved relative to the robot is minimized because we rely on a flipping stand (shown in Figure 13) that includes side stops (displayed in Figure 6). These flippers provide enough flexibility to adjust the beam position and rotation in relation to the robotic structure, despite the position the beam is placed at the start. As such, most of the error introduced by the operator is along the beam longitudinal axis. In spite of this reduction on the problem complexity, the presence of a machine vision system for the dimensional validation of the beam and its localization respectively to the robot base frame is still mandatory. This system allows to perform the adjustment of the beam reference frame programmed in the robot, over which the robot's welding trajectories will be generated later on.

Figure 13: Flipping stand

Moreover, the components to be welded in the robotic cell will also be inserted and tack welded manually by a human operator. The operator at this stage will have a valuable support provided by the projection mapping system, which will indicate the correct location for that placement based on the information taken from the CAD / IFC files. However, as it is a manual operation, the placement of the components will have some positional error when compared to the theoretical location indicated by the projection system. This difference has direct implications in the trajectory to be performed by the industrial robot and will affect the quality of the finished product. Due to these characteristics, it is also necessary to provide the robotic system with a vision system capable of detecting the joint to be welded, and in particular to validate the positioning of the part inserted by the human operator.

To circumvent these problems, a machine vision system was developed that relied on a 2D laser scanner (VC Nano 3D) that was attached alongside the robot welding torch shown in Figure 14. In this sense, the first effort went into the calibration of the laser scanner in the industrial robot Tool Center Point (TCP).

3.5.1. Laser Scanner TCP Calibration

For the calibration of line laser scanner sensor in the TCP of the industrial robot it was used the methodology presented in [29, 30]. This laser calibration heuristic runs in two distinct steps and it is based on the scanning of a physical sphere with known diameter. First, using different pairs of lasers scans over the physical sphere, each with different $tool_0$ orientations, it is calculated the rotation matrix between the robot $tool_0$ reference and the laser scanner reference frames. Then, keeping the robot

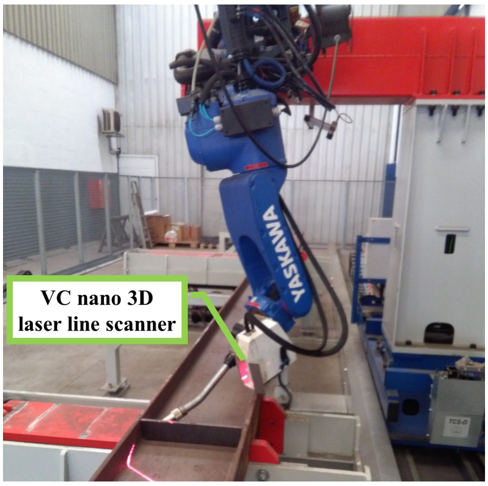

Figure 14: Hardware layout for the high precision laser based localization system for robotic welding

orientation unchanged to scan a complete sphere surface, the translation vector is calculated between the same frames, using as input the rotation matrix computed in the first step. For more detail on the followed methodology please refer to the works described in [29, 30].

3.5.2. Laser Vision System for Beam Localization

Due to the manufacturing tolerances of the steel structures, some adjustments must be made to the robot theoretical trajectories. Moreover, the detection of the beam origin is mandatory to ensure a correct work process. The achievement of this measures is made using a base frame in the robot (normally located in a fixed position). Then a calibration process is run to detect some of the edges of the beam, as shown in Figure 15. With the information obtained in the calibration process it is possible to adapt the welds to the real parts dimensions as well as ensure a correct execution of the planned trajectories.

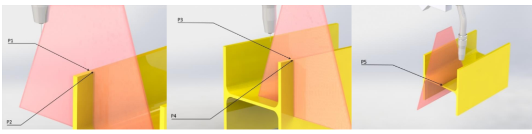

Figure 15: Beam localization procedure

3.5.3. Laser Vision System for Simultaneously Localize and Validate Manually Inserted Parts Position

Considering the problem context presented earlier, it was also developed a system capable of detecting the joints of the parts that need to be seam welded by the robot (since the operator may have introduced positioning errors when it tack weld them). As such, to validate the position of the component in the steel structure, the position of the joint was considered as an initial good estimate. Later on, by comparing the theoretical value (obtained in the virtual beam loaded from the IFC file) with the sensor data acquired with the laser scanner (example in Figures 16 and 17), it is possible to validate its position and directly compensate the trajectory of the industrial robot.

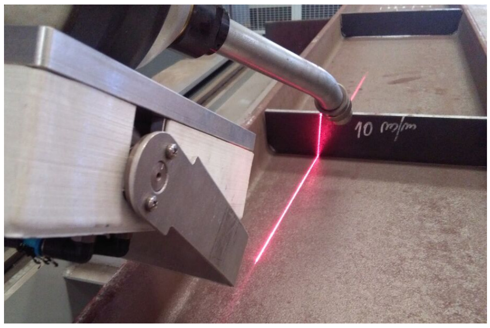

Figure 16: Detection of the joint to be welded using the 2D laser scanner

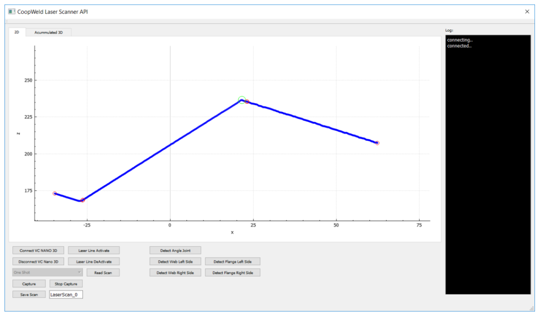

Figure 17: Result of laser scanning on a joint formed by the intersection of a reinforcement cutter and the core of the beam

For welding, this detection should ideally be performed on the first point of the welding path of the industrial robot, where the correction would then be applied. This is due to the fact that the component to be welded might have small deformations which would be tolerated by the industrial COMARC joint follow-up system installed in the CoopWeld cell. However, given the geometric dimensions of the laser scanner sensor and its scope, after some preliminary tests executed in a industrial environment, it was verified that there were occasions where it would be complicated to ensure this requirement. In particular, with regard to the guarantee of non-collision between the torch and the beam.

To overcome this difficulty, a new heuristic was designed, in which instead of extracting only one point of the joint to be welded, at least three points are detected (as depicted in Figure 18). The offsets between these three points are automatically computed based on the the theoretical length of the part to be welded. Later on, using a linear regression algorithm it is possible to compute the joint vector equation of the line and then project the theoretical welding trajectory point of the industrial robot for detecting the position of the joint to be welded.

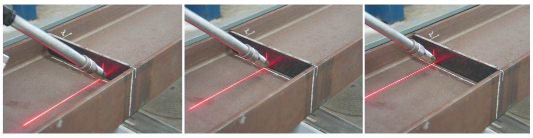

Figure 18: Illustration of the three point approach for the detection of the welding joint

3.6. *Robotic System Control and Trajectories Optimization*

In order to optimally control the robot system and its trajectories, a heuristic-based methodology using a genetic algorithm was implemented. This methodology uses the information obtained from the Computer Aided Manufacturing Software of MetroID BeamWeld and generates the optimal configuration for the robot, track and external components (in this case the flippers).

The robot platform mounted on the moving track carries a portable welding machine that is available to the human operator. The concept behind this work cell considers two stages. The first is the placing and tack weld of a given part by the operator while the second is the automatic seam welding by the robotic system. To accomplish the first task, the projection mapping system provides the user 3D marking information that is projected directly into the beam for speed up the assembly of beam attachments. This allows the human operator to perform his task in a more efficient and precise way, placing and tack welding the parts in the proper location. Then, following the norm ISO/TS 15066:2016 for collaborative robots, an add-in to the robot was inserted to fulfil the requirements of hand-guiding robotic system. As stated in Figure 19, it is possible to identify two directional buttons and one emergency stop button that allows the user to move the robotic system track and consequently acquire information for each part of the element to be produced.

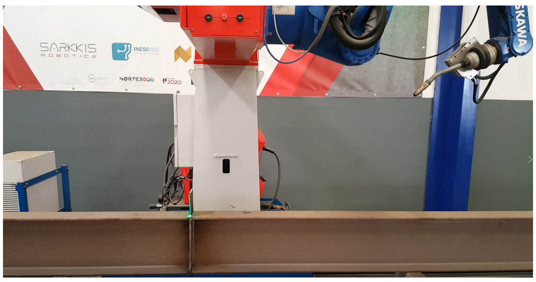

Figure 19: Hand Guiding Example

The end guiding feature allows the user to control the robotic system state in order to get a better grasp on the task and the placement that will be require next. These proposed features provide a collaborative work cell between the robotic system and an human operator.

The optimal TCP pose of the welding torch is reached based on a multi-parameter cost function that tries to minimize velocities, changes of configuration and robot / track effort, while maximizing the system range for future tasks. Once this pose is optimized, then a probabilistic path planning algorithm is used to compute a collision-free path that guides the robotic system from a given pose to the goal destination.

4. Robotic System for Welding

The current work is focused on the design of a collaborative robotic cell for structural steel beam welding. The robotic system is composed by a welding robot attached to a mobile track. In order to perform the rotation handling of the beam, there are also two flippers that can move and rotate the beam. Furthermore, all the security requirements are complied by using precise light barriers, emergency buttons and force sensors.

The CoopWeld[3] work cell is presented in Figure 20 and a demonstration video of its operation is available at[4].

Figure 20: CoopWeld: Beam Welding Work Cell

This work cell was designed based on the principals of collaborative robots as its components were adapted to better integrate with a human operator. Furthermore, the design was also an outcome of a genetic algorithm for work cell design and job validation. In this regard, an optimization technique was used to ensure the robot position that promotes the robotic challenge of the cell as well as the supporting structure.

4.1. *Welding Work Flow*

The collaboration between the human operator and the robotic system is highly enhanced in this work cell regarding the preparation stage of the tasks. Furthermore, this welding cell was designed and developed to be flexible and extensible in order to allow manual operation, semi-automatic collaboration and fully automated welding. Therefore, each job to be completed using this system can be divided in a set of steps.

[3] `https://www.coopweld.com`
[4] `https://youtu.be/3L0JBA9ozFA`

First there is the need to identify the BIM file that will carry the required information for the job. Then an analysis on this file is performed and crucial welding operations are identified and converted into tasks. These tasks then demand cooperation between the robotic system and a human operator. While the first is responsible for automated welding tasks (final stage of the job), it is also crucial for projection mapping tasks for helping the operator during its tack weld operations. Here we need to have a close relation between both ends of this collaborative system, hence the developed HMI is relevant to easily allow the communication between them and the separate portable welding device allows the job completion in a efficient way.

The optimization of poses and the insertion of a collision-free path planner gives the ability of welding always in horizontal vertical position (PB) which contributes for a cleaner weld (an example of the final result is presented in Figure 21).

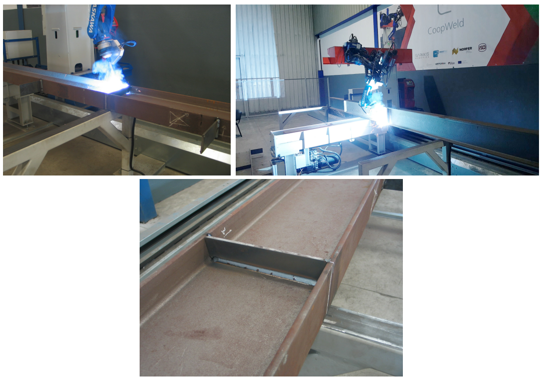

Figure 21: Seam weld of a beam attachment performed by the CoopWeld work cell

4.2. *Robot Welding vs Traditional Welding*

Focusing on usual beam welding tasks it is possible to perform a comparison between robot efficiency when compared to traditional welding operators. In order to do so, we've subjected both traditional operators and the designed robotic system to perform the complete welding procedure on some beams (Figure 22 shows the test scenarios).

Figure 22: Test scenarios for two beams

For the first test case, we have a total assembly weight of 383.26 kg. This is a simpler challenge as the total weld length is 2.56 m with a throat size of 6 mm. The complete deposited material in distance is 4.90 m, corresponding to a weight of 1.11 kg. For the second test case, we have a total assembly weight of 1052.78 kg. The total weld length is 12.72 m with mixed throats of 6 mm and 8 mm. The deposited quantity is of 24.55 m in a total of 5.24 kg of solder.

Regarding the welding quality, both test cases present similar results. The weld parameters are also consistent and similar for both the operator and the robotic system. The only key advantage during the welding procedure is related to system repeatability and endurance. Despite the fact that real welding time is similar, the robot can ensure non-stop operation while the operator fatigue and motion along the beam tends to slow the process and deteriorate the overall welding quality.

The most contrasting factor is the total operation time. The proposed system provides enough information and automation to eliminate placing errors (that require future adjustment) and the re-position of components such as beams or secondary parts. Once again, referring to the presented test cases, the first one corresponds to a robot welding time of 18 minutes and 11 seconds in a 49 minutes and 58 seconds overall cycle time. The traditional operator here achieves welding times bounded between 18 and 21 minutes and a total cycle time around 132 minutes. For the second example, we have a robotic welding time of 85 minutes and 2 seconds on a total cycle time to 116 minutes and 49 seconds versus a operator welding time between 90 and 100 minutes and a total cycle time around 310 minutes.

Analyzing the results achieved by proposed CoopWeld work cell, it is notorious the improvement that it can give in the overall production. Moreover, the efficiency of the machine and its ability to operate continuously and with high repeatability are the greatest benefits when compared to traditional welding using human operators.

5. Conclusions and Future Work

Throughout this article we presented a solution regarding robotic welding enriched by the concept of human and robot collaboration for providing a wide range of flexibility for being applied to other robotic systems with the same purpose. This solution complies with the safety requirements for collaboration between robotic machinery and humans, having already been applied in an industrial use case for structural steel beam welding.

High redundancy robotic systems commonly lack in flexibility regarding interoperability between human and robotic operators. Hence, the output of this project is clearly valuable as it presents a collaborative solution based on key developments for the robotic world. The standardization of information flow via BIM, and in particular via IFC files, enables the traceability of the process and a more efficient sequencing of tasks to complete such process.

The SAR system using projection mapping techniques allowed to maximize the usefulness of the information present in the IFC file format by showing spatial alignment markings directly into the environment. Besides improving the overall productivity of the operator, it also contributes to the drastic reduction of manufacturing mistakes since the operators no longer needs to use error prune measurement tools. Moreover, by showing the specifications on demand, this HMI system also removes from the operator the burden of constantly checking the architect design, minimizing interpretation issues.

The hand guiding allows the human operator to easily control the robotic system in order to identify the parts placements. Then the real-time adjustments computed from laser corrections allow the robotic system to automatically adapt the information retrieved from the BIM. Moreover, this particular welding cell takes advantage of the usage of multiple optimization algorithms regarding robot control and operation management. The usage of an optimal positioning planner allows to perform welding operations in horizontal vertical position (PB). This contribution has been highly valued within the industrial environment due to its effectiveness in producing cleaner results and can be extended to any other system or operation. Future perspectives for this kind of application are mainly directed to its scalability, namely its deployment in work cells with higher complexity that may include higher degrees of freedom and also dynamic collisions with the environment.

In conclusion, the collaborative robotic welding system presented maximizes the usefulness of BIM for producing optimized information flow and is able to perform complex and optimal welding tasks alongside human operators.

Acknowledgments

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A.2 Optimal Automatic Path Planner and Design for High Redundancy Robotic Systems

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Optimal Automatic Path Planner and Design for High Redundancy Robotic Systems

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Abstract

Purpose of this paper - In the vast majority of the individual robot installations, the robot arm is just one piece of a complex puzzle of components, such as grippers, jigs or external axis, that together compose an industrial robotic cell. The success of such installations is very dependent not only on the selection of such components, but also on the layout and design of the final robotic cell, which are the main tasks of the system integrators. Consequently, successful robot installations are often empirical tasks owing to the high number of experimental combinations that could led to exhaustive and time-consuming testing approaches.

Design/methodology/approach - A newly developed optimized technique to deal with automatic planning and design of robotic systems is proposed and tested in this paper.

Findings - The application of a genetic-based algorithm achieved optimal results in short time frames and improved the design of robotic work cells. Here we show that a multi-layer optimization approach, which can be validated using a robotic tool, is able to help with the design of robotic systems.

Practical implications - The usage of the proposed approach can be valuable to industrial corporations, as it allows for improved workflows, maximization of available robotic operations and improvement of efficiency.

What is original/value of paper - To date, robotic solutions lack flexibility to cope with the demanding industrial environments. The results presented here formalize a new flexible and modular approach, which can provide optimal solutions throughout the different stages of design and execution control of any work cell.

Keywords: Optimization, Robotic Systems, Meta-heuristics, Industrial Environment

1. Introduction

The concept of Industry 4.0 promotes the use of robotic solutions, because they provide sufficient flexibility to be considered re-configurable automation technologies. To date, the main challenge lies in the creation of correct frameworks able to cope with the existent industrial demands for integration of collaborative or standalone robotic systems' solutions (Pedersen et al. (2016); Sauppé and Mutlu (2015)).

Graetz and Michaels (2015) analyzed, for the first time, the economical impact of industrial robots and concluded that robots significantly added increased value to industries. Unfortunately, despite the recognized critical role of robots in science and industry, there are still major obstacles to overcome to fully implement this technology in factories, namely robotic programming (Pan et al. (2012)). In fact, the vast majority of the over 2 million industrial robots currently in use are still programmed on-line via the teach pendant approach. This is due to the lack of absolute accuracy and the problems associated with generating automatic collision-free tool trajectories for redundant systems. The integration of robots in work cells with extra degrees of freedom, such as external axis and positioners, further adds complexity to the task of robot programming.

Unsurprisingly, projects focused on tools for motion control and robot planning assume an ever-growing importance, in order to comply with both industrial requirements and efficient machinery control. The geometrical approach based on linear parameters, such as length of an operation or relative position of that operation in a given object of interest, is the most commonly used approach in industrial environment to deal with the expanding number of add-ons in the robotic system.

The use of the geometrical approach in industrial environments is rather relevant, because it allies the benefits associated with fixed robots and the possibility of extend its area of operation. Furthermore, the usage of these algorithms can ensure a higher range of solutions, in order to complete a given task with a more complex system.

Another crucial issue to be addressed is related to the specification/design of high redundancy robotic systems. This is a complex problem that is directly linked with the efficient execution of the developed solution. The work cell design is a key topic in robotics, that comprises, among others, robot selection and fixture design, which together enable the optimal completion of industrial tasks required from the robotic solutions.

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The work presented here focused on optimization techniques developed to deal with the optimal automatic path planning for high redundancy robot manipulators and the design of such systems. The approach will include not only the geometrical constraints, but also processes and work cell constraints, such as speed, on-arm fixtures management (cables) and machine safety. The developed and implemented algorithms are generic enough to assure its applicability to several scenarios.

The current paper is organized into seven sections. Section 2, Related Work, presents a brief overview on the current state of the art in robotic planning and optimization approaches. Section 3, Implemented Methodology, proposes a flexible solution framework for robotic work cell design and control. Section 4, Multi Layer Optimization, depicts the proposed solution and its main features. Section 5, Experimental Validation, presents the results obtained when the proposed approach is used to address a scientific question. Section 6, Industrial Validation, shows the effectiveness of the proposed approach in real industrial scenarios. At last, Section 7, Discussion and Future Work, critically assesses the contribution of the proposed solution, while outlining envisioned future improvements of the proposed solution.

2. Related Work

As the field of robotics expands, the need for highly autonomous and efficient methodologies to address prominent problems in the industry also increases. Over the years, there have been multiple studies focused on robot motion planning and task management. Motion planning is a key area of robotics, and it comprises path planning algorithms, configuration space discretization strategies and related constraints. Task management is an area with increasing relevance in robotics, as the optimal scheduling and step definition of a given task is desired to reduce both cost and expended time.

There are two main approaches for motion planning: reactive (Overgaard (1996); Belkhouche (2009)) and non-reactive or deliberative. Most robotic solutions are based on non-reactive path planners. These have the ability to define a path between two points.

Within this group, there is a further sub-division into sampling-based or discrete optimal planners. Sampling-based planners are commonly used in robotic applications. This concept relies on avoiding obstacles zones iteratively over time (e.g. Probabilistic Roadmaps or Rapidly-exploring Random Tree - Karaman and Frazzoli (2011); Moll and Kavraki (2006); Yoshida et al. (2008)). Discrete optimal planning focuses on creating complete paths. These require a pre-processing of all possible configurations that the robotic solution may reach and ensure a faster execution time. Examples of these planners are the A* and its variants (Zhang and Zhao (2014); Blackmore and Williams (2006)).

Despite the relevance of the topic for the research community, the use of automatic path planning in industrial scenarios is almost null. This is mainly due to memory management problems and delay in obtaining results. Path planners to be computational viable require space discretization. Hwang et. al explained the key steps and overarching hypotheses concerning the robot's surrounding environment discretization process (Hwang and Ahuja (1992)).

Once the surrounding environment of the robot is detected, there is a need to define a configuration space for the same robot. First, one needs to consider how to transform the 3D space into a discrete space of configurations. Then it is equally important to consider the kinematics of the selected robot. This will subsequently allow one to associate the current state of the robot with a Cartesian pose. Several studies have looked into approaches for autonomous and motion controlled manipulator arms, but the algorithm proposed by Yao et al. (2008) has been critical for integration of obstacles avoidance.

More recently, there have been various efforts towards the unification of kinematic and planning solutions. Notably, the Robotic Operative System (ROS) that is an open-framework with a wide range of solutions for robotic applications ROS (2019). Inside ROS there are multiple solutions for robot kinematic and planning, namely, OpenRAVE and the Open Motion Planning Library (OMPL) part of the MoveIt! software (OpenRAVE (2015); OMPL (2019); MoveIt! (2019)).

Another aspect of robotics in need for optimization is task management, which involves the integration of the motion planning in the work-cell context, technological process limitations, external devices interfaces and automatic work-cell calibration. There is no optimal tool to create an action sequence to complete a given task (currently handled by human experience). However, some studies have suggested the use of optimization functions as potential solution to this problem (Bennewitz et al. (2001); Alatartsev et al. (2015)).

Furthermore, the work-cell design in robotics is also an expanding field in need for optimization. Work-cell design comprises, among others, robot selection and fixture design. Cheng pointed out some of the simulation tool's advantages when developing a robotic work-cell (Cheng (2000)). Others have claimed the development of powerful methodologies to handle machining and welding challenges (Andrisano et al. (2011); Hauer et al. (2009)).

Therefore, it is clear that despite its importance, existent robotic systems are focused on solving individual and specific necessities and there is no optimal tool to properly design a generic robotic work cell. The most generic optimal design methodology described thus far was presented by Kamoun et al. (1999) when they presented an approach concerning the display of equipment over a given area. However, this work only considered previously selected equipment and did not include the optimal selection of such equipment.

There is a need to develop intelligent robots, so they can become highly efficient operators that are able to adapt to a wide range of problems. To date many approaches have been considered to address the industrial challenges. To this regard, robots present themselves as key components for the optimization of manufacturing processes. Some studies have been conducted to validate the efficient use of robotic solutions and the need to define a selection method for system configuration (Komašilovs and Stalidzans (2012); Komasilovs (2013)).

Importantly, the concept of optimization is highly associated to robotic operations. Robots help to reduce the cycle time of assembly lines and enhance quality assurance compared with handmade production. Consequently, efforts have been made towards implementation of intelligent robots for increased efficiency and to optimize the execution of a given task. In particular, optimization techniques have emerged and are continually subject of improvements within the scientific community working on cell configuration and trajectory planning (Čejka and Černohorský (2016); Mombaur et al. (2014)).

Robotic systems are becoming highly efficient operators. Thus, its optimal design and motion planning are key steps to ensure industrial productivity and success.

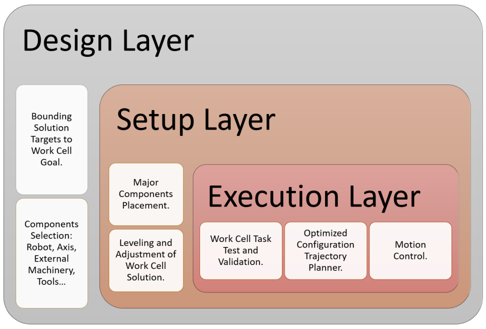

Figure 1: Cascade Multi Layer Diagram

3. Implemented Methodology

The proposed methodology intends to provide a viable solution for vertical integration from the corporation management decision of shop floor upgrade to technical design and control of an optimized work cell to reach the desired goals.

The information flow from decision to work cell and ultimately to system machinery and operators has been developed throughout the years to achieve a more efficient data transmission from high level tiers in a corporation to the low levels of production and manufacturing.

Another key part of smart manufacturing is related to automation along the several decision and execution stages of a work cell. Here, we propose a three layer solution that can be applied to decide the optimal work cell to achieve the defined objectives by the industrial entity.

The real application of the proposed solution intends to deal with layout and components constraints while validating the usage of the work cell to complete the required tasks. The concept of Industry 4.0 is commonly associated to the concept of modularity and flexibility. Therefore, the development towards industrial revolution and acceptance should be build on top of inter-operable and decentralized solutions able to adapt to any given environment.

Hence, the development of the work presented here consists in a well defined and divided multi-layer solution applicable throughout the complete design, setup and execution stages for a given work cell. Each stage is flexible enough to be applied to multiple scenarios. Thus, we defend a cascade integration of the three stages as one can function as a decision tool from the other as presented in figure 1.

Summing up, the design stage can be seen as a high level application to decide which components to select for a given shop floor project. However it requires an algorithm for optimal placement of those components, which can be provided by the setup stage. This intends to classify random positions for a selected list of components in order to maximize the efficient undertake of the predefined tasks. The classification is based on work cell execution completion, and, therefore, an execution stage analysis is required. This classification is achieve using a multi-parameter cost function.

4. Multi Layer Optimization

The selected algorithms follow an ideology of heuristic-based solutions and share a common goal that is the minimization of effort and maximization of present and subsequent poses. A cost function was developed based on seven features. This work is a self-improvement of one previously published by our group Tavares et al. (2018).

To face the proposed challenge, four mains optimization techniques were selected: Linear Scanning, Genetic Algorithms, Simulated Annealing and Potential Fields. The relevance of each one has been discussed previously Tavares et al. (2018). Nevertheless, it is important to revisit these results.

The goal was to optimize the robotic system pose to complete a set of operations. Each of the proposed methods returned a heap storing the best outcomes of the cost function. Considering that each solution results were an array of joint values throughout the kinematic chain, a dynamic structure was built upon the map generation. Every heap element followed the parameters defined within that same structure. The results are quoted in table 1.

Table 1: Results summary of the optimization methodologies comparison

Optimisation Methodology	Reach-ability (%)	Time consumption (s)	Cost Value
Linear Scanning	100%	18.031	0.103
Genetic Algorithms	100%	1.022	0.098
Simulated Annealing	96.4%	0.740	0.147
Potential Fields	81.4%	0.412	0.134

This study allowed to verify the relevance of using genetic algorithms in robotics, as this algorithm reaches a viable solution for all cases with concomitant reduction of time and computation effort. Thus, we proposed a solution built using genetic-based algorithms.

The design stage promotes multi chromosome genes with equal dimension to the number of work cell components. Each hypothesis is coded through a digital key and the crossing and mutation commonly associated to this kind of algorithms is based on the modification of this key.

The setup stage multi chromosome genes that define the relative position of a component in the shop floor.

This data is numerical, therefore the crossing and mutation of it is similar to typical genetic algorithms.

Finally, the execution stage intends to determine the best posture and configuration for the entire motion system within a work cell. Each body that inserts movement into the system is coded as a part of a multi dimension array that describes current joint positions. These stages will be described next.

4.1. Execution Layer

The low level tier of the proposed optimization is related to strategy planning (motion planning) and validation of clean trajectories for a given work cell and task.

In this work, a customized genetic algorithm is used, as this algorithm provides a better solution in a faster way. For each work cell, a set of genomes (population) are created with N genes related to the number N of motion inserting components within the work cell. Each gene is responsible for the storage of the hypothetical value related to the component motion.

Then, by transforming the set through crossing and mutation inside the population, a random range of hypotheses are tested, selecting the most suitable for each challenge.

Focusing on the specification for the optimization algorithm, it is important to recapture its key stages and features. Previously in the already mention work (Tavares et al. (2018)), the hypotheses were tested considering a six feature cost function that intended to minimize efforts and maximize the number of current and future poses. An extra feature was inserted to consider dynamic constraints (velocity and force minimization). Therefore the seven features used are: External Axis Motion (ExternalM), Singularities (Sing), Dynamic Constraints (Dynamic), Configuration Change (Cfg), Joints' Effort (JtEffort), Robotic Reach (Reach) and Joint Limits (JtLimit). The current equation can be defined by equation 1.

$$\sum(w_1 * ExternalM, w_2 * Sing, w_3 * Dynamic, w_4 * Cfg, w_5 * JtEffort, w_6 * Reach, w_7 * JtLimit) \quad (1)$$

w_1 to w_7 are just scaling weights related to the importance of the respective parameter. These must to set accordingly to client specifications and requirements and bounded between 0 (not relevant) and 1 (highly relevant).

On top of this optimization algorithm, a probabilistic algorithm is used as this computes a faster solution while ensuring a complete path.

4.2. Setup Layer

A recurrent challenge in all industrial work cells is the placement of components to ensure a clean global layout while validating each component functionality and contribution for the work cell efficiency. This is a double stage process, where: (1) from a macro standpoint, the relative layout is selected; and (2) the position, orientation and leveling of each component are set to complete the intended tasks.

Currently, in the industrial environment, this is accomplished by a well trained operator that based on experience and shop floor constraints is able to design the layout and work cell assembly features.

The proposed approach intends to use intelligent and flexible decision making to aid with this selection. Thus, at this layer, the components are already selected and a new genetic algorithm is used.

Our approach uses the execution layer explained previously and consequently its cost function while adding constraints to avoid components overlapping. This can be described by a sum of two terms (equation 2).

$$\sum(w_1 * ExecutionCost + w_2 * CollisionValidation) \quad (2)$$

The ExecutionCost term of the previous equation is defined by a set of complex sums of multiple tasks to be validated. Considering welding work cells this would be a set of N beam/tubes/profiles with a defined number M of welds that are require to be produced within the work cell. Thus, this term can be defined by equation 3.

$$\sum(Execution_{op_{1,1}} + ... + Execution_{op_{N,M}}) \quad (3)$$

The term $Execution_{op}$ can be defined as the return value of the Execution Layer affected by another important consideration to be added here regarding the evaluation of the operation failure. This is included in the classification automatically, since for unreachable targets, the cost function of the Execution Layer return a significantly high value.

The CollisionValidation term is simply a two value function to describe the proposed placement as a collision free solution (CollisionValidation = 0) or not (CollisionValidation = 1). Then the weights w_1 and w_2 are merely a tool to reject solution on which CollisionValidation = 1, since that $w_2 >> w_1$. This way a maximum limit threshold is reached in colliding cases, and therefore, they are discarded.

4.3. Design Layer

The ultimate high tier layer of the proposed approach is related to full work cell design and specification. This is accomplished by using a set of constrains and components database with possible robots, axis, external positioners and tool.

Currently, the developed algorithm receives the following as an operation input: parts to be handled, distance of operation, number of robots, usage of external axis/positioners and placement interval for the parts to be handled. And outputs a set of classified possible partial (in cases where there is no possible solution for all challenges) or total solutions.

Once again, to do so, it is used a genetic algorithm. To compute this layer, each gene is composed by a list of robots of equal size to the number of robots selected, an external axis chain and a set of positioners, if applicable, as well as a tool suitable to complete the operation type (welding torches for welding, cutting torches for cutting, grippers for picking operations, etc). Upon gathering this information, a virtual work cell is created.

Then, our proposed approach uses a cascade software to integrate this hypothetical virtual work cell and validate it by using the Setup and Execution Layers. Thus, the value of each hypothesis may be defined by the optimal output of the Setup Stage. This allows for complete definition of an entire workstation based on just a couple of constraints.

5. Experimental Validation

To ensure the validation of all methodology stages, a scientific scenario was selected and was composed by: a external circular ring, a robot platform moving along the ring, a robot, a random attached tool on top of the platform and a fix table. The simulated work cell is displayed in Figure 2.

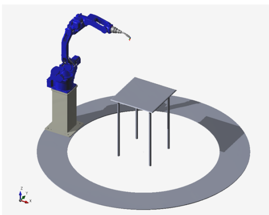

Figure 2: Testing Scenario

The circular ring is a simplistic representation of an external axis. The robot platform is a simple stand with a square base. The selected robot was a Motoman MA1440 and the attached tool is an ABICOR W500 welding torch. At last, the fix table will serve as object of interest. The ring and the table are centered with the origin of the simulated environment.

The experimental validation was conducted using a simulation framework that allowed the creation of virtual work cells and testing of the full extent of the proposed approach.

5.1. Execution Layer

Four clear poses were defined, each pose defines one of the corners of the table. Another relevant data is the starting point. For each pose the starting point was defined by a zero value array that visually results in the posture seen in Figure 2. The solution are displayed graphically in Figure 3.

Each solution is given concerning only the joints that insert motion, and, thus, in this case is a set of seven values, one allied to the value of the circular track, and six related to the value of each robot joint for the given pose and this order. The results for each pose are presented in the following tables.

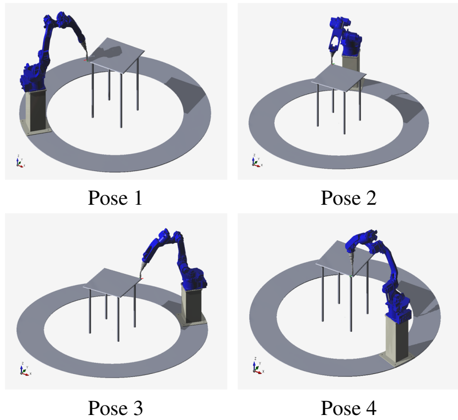

Figure 3: Solution graphical visualization

Table 2: Top results for Pose 1

Index	Joint Array	Cost
1	[45.1, 0.1, -8.4, -36.7, -0.2, -22.8, 0.3]	0.068
2	[44.8, -0.2, -8.4, -36.7, 0.4, -22.8, -0.8]	0.069
3	[45.5, 0.4, -8.5, -36.7, -0.8, -22.8, 1.5]	0.071

Table 3: Top results for Pose 2

Index	Joint Array	Cost
1	[-69.1, -8.1, -35.3, 0.0, -12.0, -73.9, 153.0]	0.282
2	[-20.8, 8.2, -35.4, 0.0, 12.1, -73.9, -152.9]	0.282
3	[-69.5, -8.3, -35.4, 0.2, -12.2, -73.9, 152.7]	0.283

Table 4: Top results for Pose 3

Index	Joint Array	Cost
1	[-135.0, 0.0, -8.4, -36.7, -0.1, -22.8, 0.1]	0.068
2	[-135.3, -0.3, -8.5, -36.7, 0.6, -22.8, -1.1]	0.070
3	[-134.6, 0.3, -8.5, -36.7, -0.7, -22.8, 1.3]	0.070

Table 5: Top results for Pose 4

Index	Joint Array	Cost
1	[159.3, 8.2, -35.4, 0.1, 12.1, -73.9, -152.8]	0.282
2	[158.9, 8.1, -35.3, -0.1, 11.9, -73.9, -153.2]	0.282
3	[111.0, -8.1, -35.3, -0.1, -12.0, -73.9, 153.1]	0.283

5.2. Setup Layer

To evaluate this tier of the proposed approach, the stand of the robot was deleted from the scene and an assumption of a pending robot as made in order to determine what should be the optimal position for the robot concerning its height relative to the floor.

Thus, this was a one-chromosome problem (the height of the robot). The genetic algorithm solutions were bounded from 0mm (imposed by the floor) and 1500mm. The initial population was 100 with a crossing percentage of 50% and a mutation rate of 10% The testing positions remain the same as the previous subsection (the four corners of the table).

In Table 6, the top three results for the height consideration are presented. The cost value on the table are the result of equation 2. Figure 4 displays the graphical outcome for the robot configuration at each corner.

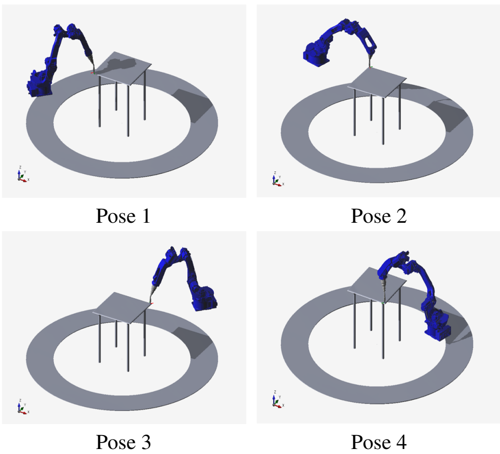

Figure 4: 3D simulation shots of these 4 Poses of interest.

Table 6: Top results Robot Height selection

Index	Robot Height	Cost
1	807mm	0.452
2	802mm	0.452
3	813mm	0.453

5.3. Design Layer

The validation of the design layer on this work was related to the choice of robot. To this regard there were three initial options: Motoman MA1440, Panasonic TL1800 and Comau Six. The test conditions (poses) remained the same. In Table 7, the classification results for each robot for the design challenge are presented.

Throughout the analysis process all robots were able to provide solutions. Nevertheless, the motoman MA1440 and the Panasonic TL1800 achieved the more comfortable postures due to their mechanical constraints. The results are stated in Figure 5.

Table 7: Classification of Circular Ring and its positioning

Index	Robot Tested	Cost
1	Panasonic TL1800	0.674
2	Motoman MA1440	0.700
3	Comau Six	0.983

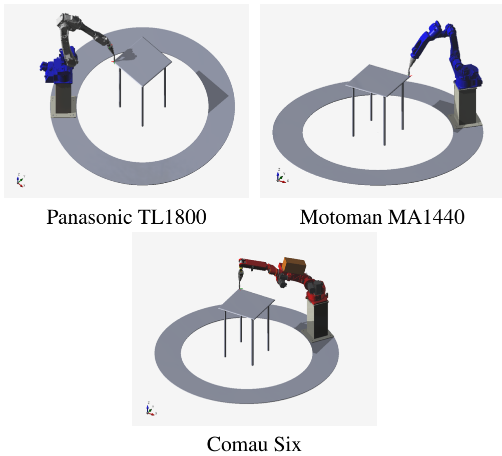

Figure 5: 3D simulation shots of the 3 robots' posture over the promeninent reaching problem.

6. Industrial Validation

The industrial validation is based on two industrial scenarios, both presented in the two subsection presented below.

6.1. CoopWeld

CoopWeld is a collaborative cell that incorporates assisted assembly with a camera/laser projector duo and automatic welding of beams, assisted with pneumatics flippers for the beam rotation. The chosen robot is a Motoman MA1440 positioned with a 90º pitch on a structure inserted in the sole external axis of the cell, a 14m track from Yaskawa (figure 6).

The main goal of this project is to promote the collaboration between human and robotic operators. The concept of collaborative system in present due to the inserting of hand-guiding of the overall motion system (axis and robot) and a projection mapping interface.

CoopWeld intends to automatically generate robotic instructions for assisted assembly and automated welding of beams. The main challenges is this work cell were to decide the relative position of the robot facing the remaining components and, upon the work cell implementation, the control of system motion through the optimization of poses.

Figure 6: CoopWeld Work Cell

6.1.1. *Optimization Approach*

To assess the multi-variable problem behind the CoopWeld work cell implementation, it is necessary to define a two layer testing group. The first layer is related to component analysis, while the second is related to component placement. In that regard a possible solution can be defined by a set of solutions (see figure 7 for a reference example).

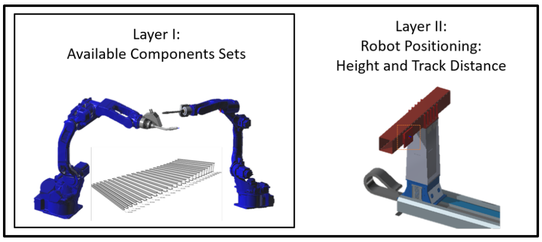

Figure 7: CoopWeld Hypothesis Set

Each hypothesis is composed by the robot, one of the welding torches and a beam.

Upon built a hypothesis based solution, the optimization algorithm for pose definitions is applied to every move gathered from a CAM software. The optimization algorithm for pose definitions can be approach in two phases. The first phase is to calculate the easiest configuration for a given pose, this includes the positioning of the robot's joints as well as any selected external axis. The second phase of the optimization algorithm for pose definitions is the path planning to the validated configuration retrieved from the previous phase. With the two phase approach, the cell is capable of executing scans and welds with a considerable rotation of the tools without the worry of collisions or irrational movements along the procedure as depicted in figure 8.

The optimization methodology required as inputs the work cell components to be tested but also the bounded limits to compute a final solution. To this regard, a distance to track from the robot placement was bounded by the interval of 0.5m to 1.5m along the y-axis (distance to the track), and by the interval of 1.5m to 2.5m along the z-axis (height to the ground).

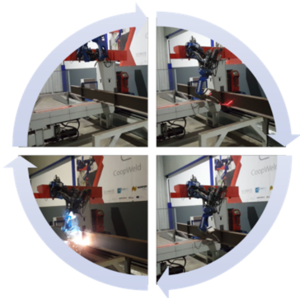

Figure 8: CoopWeld Operation Sequence

Based on the already mentioned parameters of interest, a set of possible outcome positions and components were returned for the previously mentioned elements, leading to the selection of such elements and, consequently, allowing the development of the correct scale and height of the structure that wields the robot, a key element of the whole cell.

The algorithm analyzed around 200 possible welds on more than 20 beams. Some hypothesis are shown as an example in figure 9. The associated cost are stated in table 8.

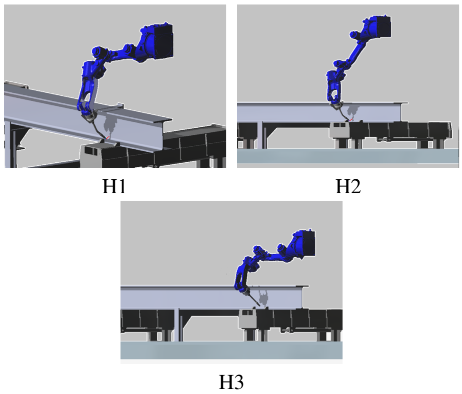

Figure 9: Solution graphical visualization

Table 8: Cost results for H1, H2, H3

Hypothesis	Torch	(Y, Z) mm Position	Cost
H1	Round	(-959, 1926)	0.186
H2	Round	(-959, 2426)	0.311
H3	Straight	(-1002, 1626)	0.278

The optimal result led to the implementation of this robotic solution in the client industrial facility, where the round torch and the positioning of the robot at (-959, 1926) mm were the selected solutions.

6.2. Digital Factory

Digital Factory is a projected robotic cell for the manufacture of pipelines. The whole cell consists in two MA1440 robots from Motoman each mounted in a separated stand, a track of 7 m with a mounted turn, another fixed turn mounted in a stand to produce the secondary tubes to provide the divergencies in the main tube and a part warehouse to supply the production.

The main purpose for optimization usage in this project is related to placing of components over the work cell layout. The choice of components was previously set. Another important methodology application is related to the control of the robotic workstation through the complete range of operations: grasp, pick, place, cut, tack and weld.

The spatial constraints in this project were extremely demanding, given that the amount of free shop floor space available did not allowed for most non-overlapping configurations.

Every single of the previously mentioned elements were inserted in the optimization algorithm for enhancement design envisioning the best possible combination of height, rotation and distance for a smooth and effortless transition between work stations, thus returning the optimal work cell layout.

To comply with both industrial and safety requirements there is also a synchronization control unit that manages robot operation with external machinery operation. This way it is possible to process multiple projects and tasks simultaneously. The result of the optimization design methodology is explained in greater detail next.

6.2.1. Component Optimal Positioning Placement

The Digital Factory work cell design can be consider a complex challenge. Most components required optimal placement considerations while the full system should comply with all operations inherent to the work cell.

Even though most components were already selected, most placements were unknown. The fixed parts of the work cell were the input and output warehouse, the input feeder, the robotic track with coupled turn and the fixed support. Two reference planes were defined based on these components. A central plane across the center of the track and a reference plane coincident with the track exterior surface. All the remaining components should be placed on a restricted area given by the relative distance to the defining planes.

Therefore initial a set of constraints should be collect in order to provide the need input for the optimization methodology. These constrains are presented in Table 9.

The generic application of the algorithm produced results considering several scenarios while assuring the execution of the task as depicted in figure 10.

Each operation retrieved a partial cost. The sum of each operation for a hypothetical work cell layout provided the cost for the solution. Initial the population of the genetic algorithm was composed by 1000 sets of genes with 13 chromosomes. This genes were composed by:

Generic Chromosome = [$R_{1,x}$, $R_{1,y}$, $R_{1,z}$, $R_{1,r}$, $R_{2,x}$, $R_{2,y}$, $R_{2,z}$, $R_{2,r}$, W_x, W_y, FT_x, FT_y, FT_r]

Table 9: Constraints for Digital Factory Work Cell Design

Component	Constraint Description
Robot1	Robot Height relative to the floor (Z); Robot distance to central plane bounded from 0.5m to 1.5m (y). Robot distance to reference plane bounded from -1.0m to 1.0m (X). Robot Base Orientation (R).
Robot2	Robot Height relative to the floor (Z); Robot distance to central plane bounded from 0.5m to 1.5m (y). Robot distance to reference plane bounded from -1.0m to 1.0m (X). Robot Base Orientation (R).
Part Warehouse	Warehouse distance to central plane bounded from 1.5m to 2.5m (y). Warehouse distance to reference plane bounded from -1.0m to 1.0m (X). Warehouse orientation was fixed.
Fixed Turn	Fixed Turn distance to central plane bounded from 0.5m to 1.5m (y). Warehouse distance to reference plane bounded from -1.0m to 0m (X). Fixed Turn Orientation (R).

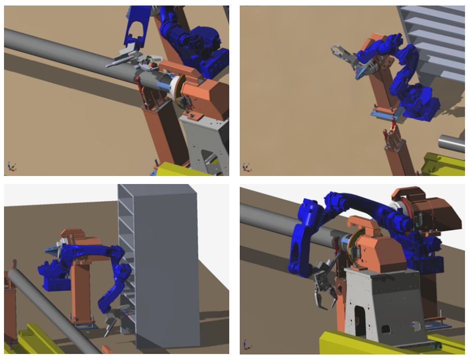

Figure 10: Digital Factory Operation Testing

Each of the initial genes is randomly generated based on the bounding constraints and from that point on, through crossing and mutation of genes, new hypothesis are tested. The rate for crossing was set to 50% and the rate for mutation was set to 10%.

Despite having the optimal results, an additional constraint was added at the end of the process to minimize the manufacturing effort of the auxiliary components. This constrain fixed the same height for both robots and redefined the remaining components around them. This led to a physical implementation of a currently working robotic cell.

This optimization returned the optimal relative position for the components, achieving a similar result to figure 11.

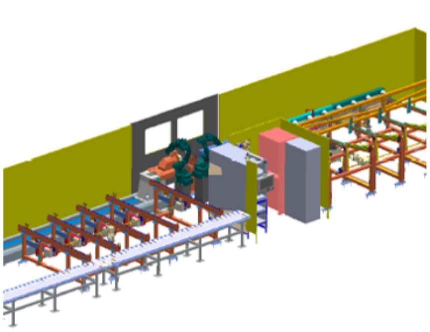

Figure 11: Digital Factory 3D Representation

7. Discussion and Future Work

Through the work presented here, a multi tier solution was developed to optimally deal with some of the most common challenges and complications in the design of robotic cells.

The three layer solution presented in this paper (execution, setup and design) allows the user to incorporate a modular solution into the design and control of a manufacturing work cell. A scientific approach is described whereby it is possible to use a genetic algorithm in all three process stages.

First, the optimization of the system posture to optimally reach a pose intends to reduce the time and joints effort of the system by moving components so that a set of goal values can be output to reach task completion.

Then, the tier responsible for component positioning is presented and tested addressing a recurrent problem in robotic work cell architecture design.

Finally, the complexer part of this solution incorporates all the above and automatically designs the work cell following some constraints. Here we identified the correct robot to use in an scientifical test case.

All these solutions are genetic based algorithms, which have proved to be a fast and secure method for robotic optimization strategies. In fact, the concept of robotic optimization and its utility in robotic work cells' design gains traction when this kind of algorithm is applied. Importantly, future tasks to be completed by the robot will be smoothly completed and the reachability issues will be eliminated. Thus, the application of this methodology can provide robotic system integrators and generic industrial end-users a design tool to comply with a wide range of operations, fixtures, constraints and components.

Two industrial application examples were also presented here to illustrate all different methodological stages of the proposed robotic approach and their possible interaction.

In CoopWeld, a set of robot positions was considered to ensure task completion. The results proved to be effective in both simulated and, more importantly, real industrial environment, where the developed work cell is currently being used for continuous welding tasks.

In Digital Factory, an higher level of requirements were considered, and the results provided a complete description of the work cell layout. The projected work cell was also implemented in the industrial environment and, despite spatial constraints and a reduce area of work, the sequence of operations inherent to the cell construction was smoothly delivered.

Although the initial industrial feedback for both implemented solutions was positive, the design stage requires some refinement to increase the database of components, so that the final outcome considers more strategies and returns a solution with higher degree of confidence.

In conclusion, a flexible, modular and generic robotic solution to work cell design and control was presented here.

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