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CALIBRATION DEVELOPMENTS FOR MULTICAMERA OPTICAL TRACKING SYSTEMS

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BIOMEDICAL IMAGING AND INSTRUMENTATION GROUP

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Título: **CALIBRATION DEVELOPMENTS FOR MULTICAMERA OPTICAL TRACKING SYSTEMS**

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ABSTRACT

Intra-Operative Electron Radiation Therapy (IOERT) is a technique for cancer treatment that delivers a high dose of radiation directly to the post-resected tumour bed or to an unresected tumour during surgery. Recently, a tracking system (OptiTrack, NaturalPoint Inc., USA) was installed into the operating room that allows for navigation and thus assist oncologists in the treatment planning of this procedure. The system is an optical tracking system composed of eight independent cameras, and then a calibration process is required for a correct tracking performance. The current state consists on calibrating just before every IOERT procedure, increasing surgery preparation time by approximately one hour.

In order to study the feasibility of defining new calibration protocols based on calibrating every certain period of time, this projects assess the temporal stability of tracking system calibrations and determines an optimum methodology for the detection of miscalibration within the tracking system.

To achieve this, software applications were developed to control the Optitrack system by means of the Application Programming Interface provided by the vendor. Also, a group of experiments were performed using developed applications to acquire tracking data.

Results show the temporal stability of the tracking system calibration during five days, and the feasibility of detecting tracking system miscalibrations by using the proposed methodology.

This study will allow the hospital to save time and resources by stablishing protocols for calibration in which calibration is performed every 2-5 days. The calibration state of the system will be evaluated before every surgery in order to determine if the system needs to be calibrated or not following a proposed methodology (with an average duration of 5 minutes).

KEY WORDS

Intra-Operative Electron Radiation Therapy, optical tracking system, calibration.

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1. INTRODUCTION

Image-guided surgery (IGS) consists of real-time tracking of surgical instruments with respect to the imaged patient anatomy during a medical procedure, providing physical relationships between instruments and patient's body structures. This approach leads to an improvement in speed, security, and effectivity of surgical procedures[1].

The purpose of this section is to provide an overview of intra-operative electron radiation therapy (IOERT) and tracking systems as an introduction to the actual scenario at Hospital General Gregorio Marañón (HGGM) where this work was developed.

1.1. INTRA-OPERATIVE ELECTRON RADIATION THERAPY (IOERT)

Radiation therapy is a type of cancer treatment based on the delivery of high energy radiation to tumour targets for stopping growth and proliferation of cancer cells avoiding, as much as possible, affectation of critical organs [2].

The most extended radiation cancer treatment is External Beam Radiation Therapy (EBRT) which combines external radiations transferred to the patient along different directions specifically established during treatment planning in order to maximize the dose in the tumour volume. The radiation used in this radiotherapy treatment is composed of photons. Other possible treatment is brachytherapy, or internal radiation therapy, where the radiation source is placed inside the patient.

Intra-Operative Electron Radiation Therapy (IOERT) is a technique that delivers a high dose of radiation directly to the post-resected tumour bed or to an unresected tumour during surgery, where the target area is more exposed (Figure 1) [3]. The radiation in this technique consists of electrons. This treatment is sometimes combined with adjuvant EBRT and chemotherapy.

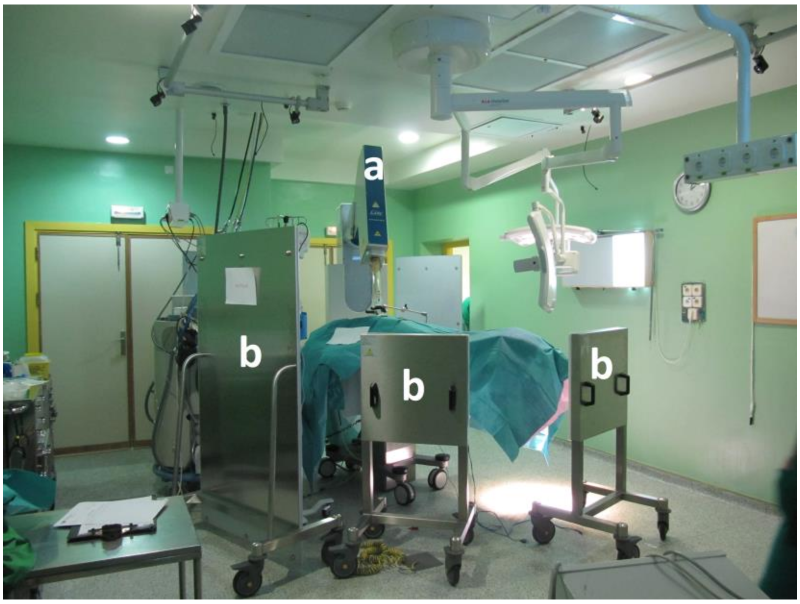

Figure 1: Operating room during IOERT. Linear accelerator (a) is prepared to emit the radiation, and lead mobile barriers (b) have been placed for shielding.

During IOERT, the radiation is produced by a linear accelerator (**Figure 1.a; Figure 2**) and conducted to the target volume by an applicator (**Figure 3**) attached to it. This setup enables a precise application of a high radiation dose while minimizing exposure to surrounding tissues, which are displaced or shielded during the procedure [4].

The main problems of IOERT are the associated organizational disadvantages that arise in many institutions: patients must be transferred during surgery to the radiotherapy department to receive the dose, or a linear accelerator (LINAC) is required inside the operating room. In late 1990s, those disadvantages were minimized with the appearance of mobile operating room LINACs, allowing the transfer of the machine to any operating room [5].

The successfulness of radiation cancer treatments depends on the correct delivery of the dose which must be adapted to the current stage of the tumour and to the target area. In order to determine the correct dose in each case, a treatment planning needs to be carried out. In EBRT this planning is simpler since tissue distribution is well known from CT images. However, dosimetry planning for IOERT is more challenging due to the geometrical and anatomical modifications produced by the retraction of structures and removal of cancerous tissues during surgery [6].

Figure 2: Mobile linear accelerator in Hospital General Universitario Gregorio Marañon.

Therefore, in current IOERT clinical practice optimal treatment parameters (high risk areas, beam energy, applicator geometry and positioning) are estimated *in situ*, in the operating room, based on previous procedures and radiation oncologists experience.

Based on the current treatment planning scenario for IOERT, it would be very useful to obtain a case record gathering experience and results for every case involving this treatment. A register of cases will cause an improved planning of new procedures. However, in order to create a case record that will reduce the current high dependency on professional expertise, a proper documentation of all procedure parameters (including applicator position and orientation, and dose distribution) is necessary.

Figure 3: IOERT applicator positioned for rectum IOERT simulation from [5].

A treatment planning software, called "*radiance*" (**Figure 4**), was proposed and developed by the BiiG (Biomedical Imaging and Instrumentation Group) in collaboration to the company GMV. This software allows the simulation of the IOERT procedure by displaying the position of a virtual applicator superimposed on the patient's computed tomography (CT) or magnetic resonance (MR) image [7]. Apart from the combined display, dose-to-volume curves for every affected organ are shown based on the CT scan units for dose simulation. Using this approach, best parameters can be determined in order to maximize the dose deposit on the target area, while minimizing it on those areas wanted to be protected from radiation [8].

However, the modification of patient's geometry during surgery leads to changes of the pre-surgical radiation treatment planning depending on the actual scenario. In order to produce a real-time accurate description of the IOERT scenario, a tracking system must be included in the operating room. At HGGM, the radiation therapy operating room has been equipped with an optical tracking system. The purpose of this tracking system is to track and record the position of the IOERT applicator with respect to the patient's anatomy [6].

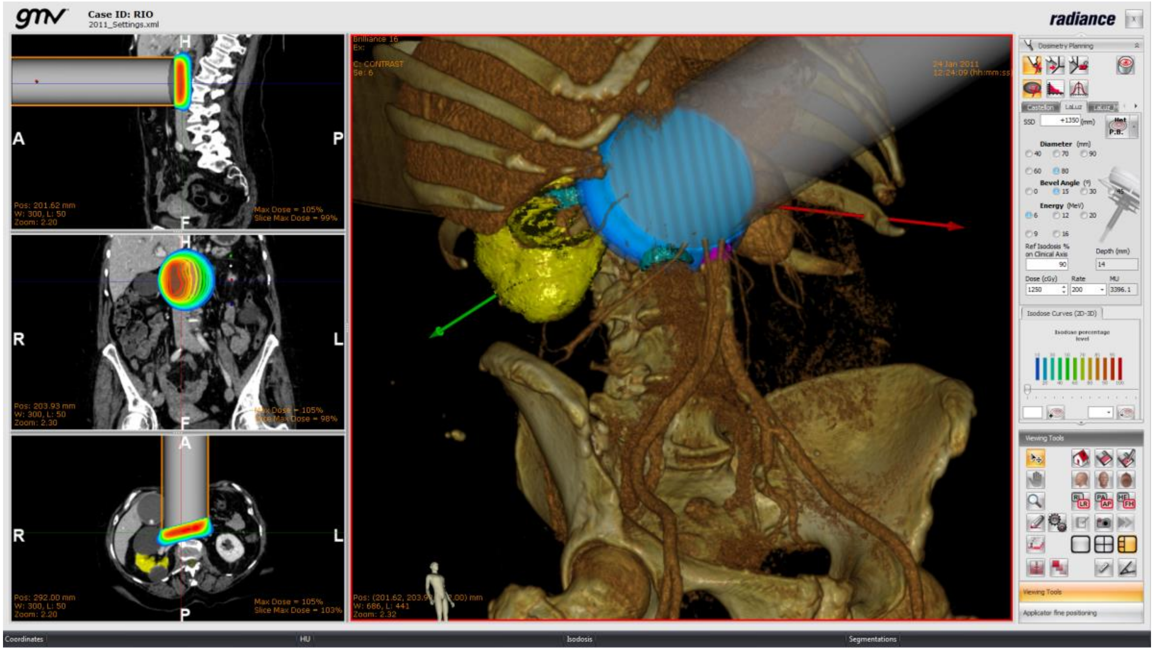

Figure 4: Screenshot from radiance where both 3D virtual position of the applicator and the dose distribution in 2D image planes are displayed.

1.2. TRACKING SYSTEMS

Tracking devices play a key role on image-guided surgery by determining the positions of objects in real-time with respect to patient's anatomy.

The history of tracking systems begins in the late 1920s with the invention of the stereotactic frame (**Figure 5**), used for neurosurgical applications. Developments in computed tomography and magnetic resonance imaging by the mid-1980s led to frameless stereotaxy, allowing smaller incisions and reducing patient discomfort and preparation [9].

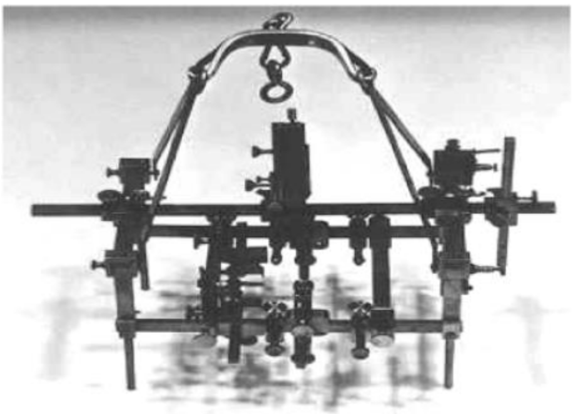

Figure 5: Stereotactic frame from [9].

Although first tracking systems were mechanical, other technologies came up using optical and electromagnetic properties for the tracking of specific markers. Nowadays, these innovative systems are broadly used in clinical applications, but the best choice of tracking device is highly application dependent.

Optical tracking systems (OTS) offer a larger working volume, higher accuracy and more reliability than electromagnetic (EM) tracking devices, which are susceptible to distortions from nearby metal sources [9], [10]. However, since the main limitation of OTS is that line-of-sight is required between tracker cameras and optical markers, EM tracking systems (EMTS) will be indicated for those applications related with tracking objects within the body, such as catheters or needles based procedures.

1.2.1. OPTITRACK OPTICAL TRACKING SYSTEM

At HGGM, image-guided IOERT equipment uses the optical system OptiTrack (NaturalPoint Inc., OR, USA). This system meets the characteristics needed for its use to provide real-time information during IOERT treatments. Those characteristics are: large working volume, high accuracy and good distribution of cameras in order to maintain objects tracked at any time avoiding occlusions. In addition, it can handle up to ninety six cameras, enabling an increase in the number of cameras if needed to avoid even more line-of-sight obstructions during surgical procedures.

The installed system consists of eight cameras surrounding the operating room covering a large volume of space with the objective of tracking the position and orientation of the IOERT applicator (**Figure 6**). The number of cameras has been determined taking into account the working space dimensions and possible occlusions.

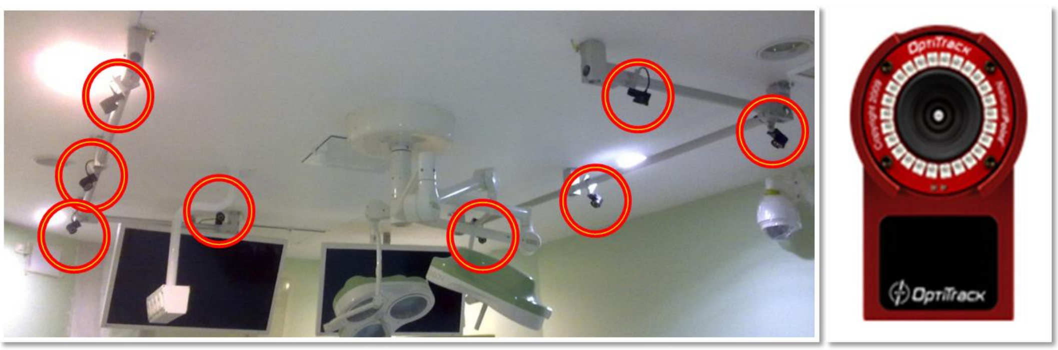

Figure 6: Distribution of cameras in HGGM operating room.

Each of the eight cameras (model OptiTrack Flex 13) has 28 light-emitting diodes (LED) with 1280x1024 pixels image size and can work up to 120 frames per second. They detect the objects that reflect infrared light (800 nm long), filtering the rest from the spectrum (**Figure 7**) [11].

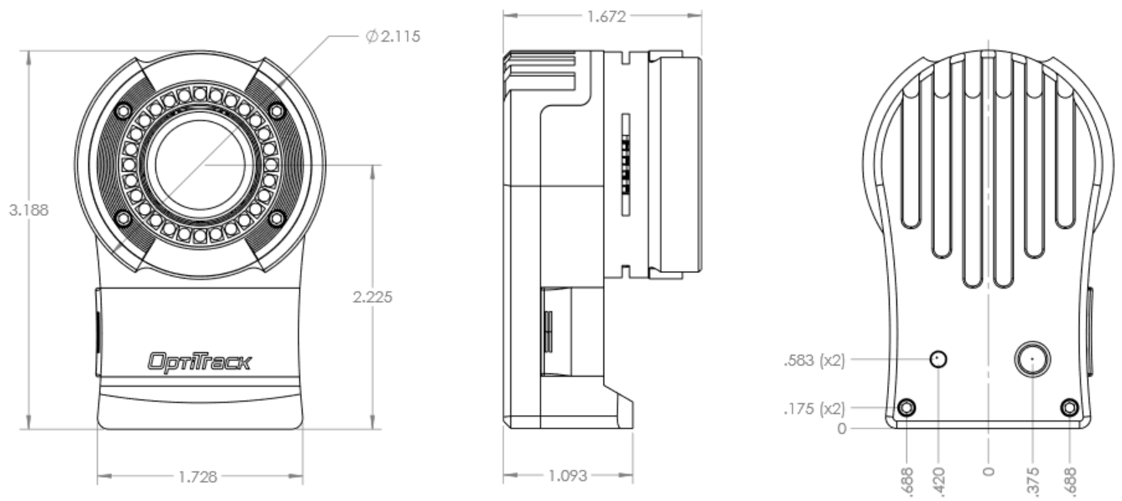

Figure 7: Technical drawing OptiTrack Flex 13 from [11].

The tracked objects, called rigid-body tools (**Figure 8.a**), have special infrared-reflective balls, called reflecting markers (**Figure 8.b**). Markers are located in the 3D space by geometric triangulation. Triangulation mathematically determines three-dimensional coordinates for an object given two-dimensional views (projections) of it from multiple cameras based on the intersection of the projected rays of every camera (**Figure 9**) [12].

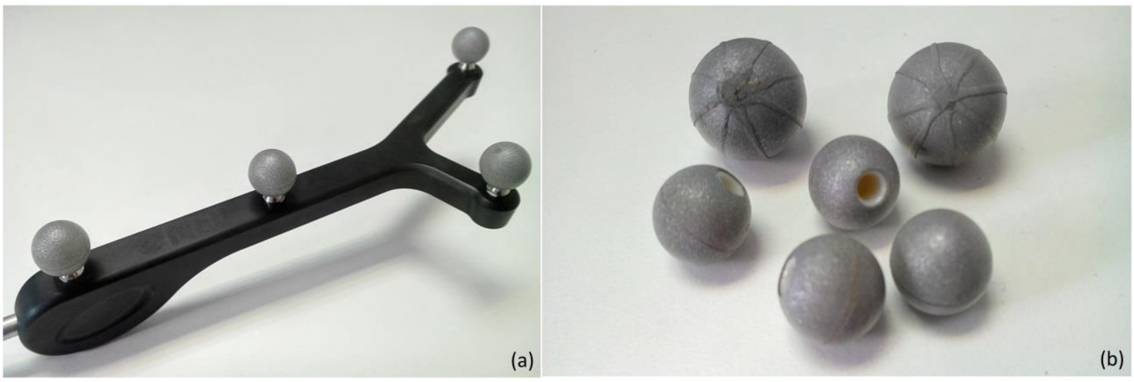

Figure 8: Optical tools: (a) NDI Polaris Pointer tool; (b) Spherical passive optical markers.

In order to obtain information about the position and orientation - 6 degrees of freedom - of a rigid body at least three markers (points) must be tracked. In general, the geometry defined by the markers in the rigid body (tool) cannot change in time, that is to know, distances and angles between them are maintained in order to be tracked.

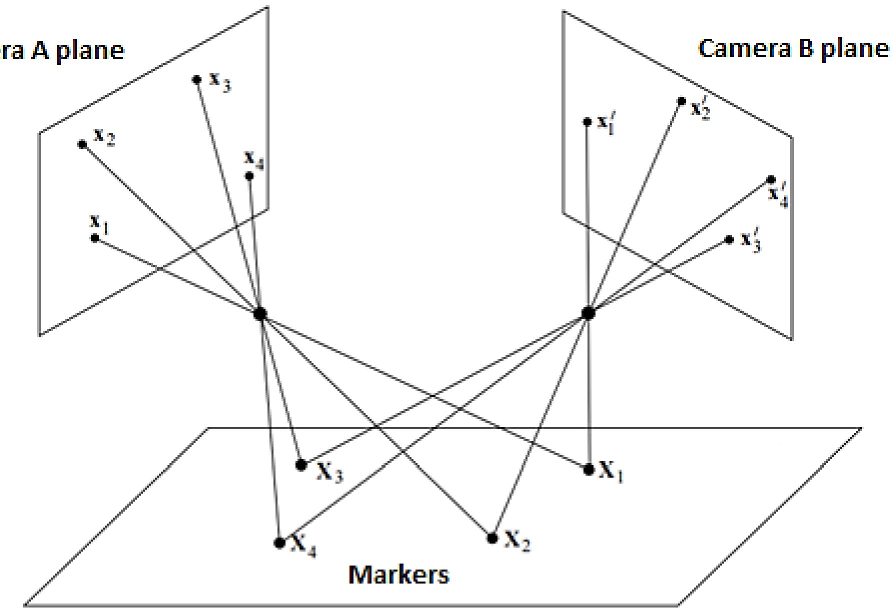

Figure 9: Intersection of projected rays of two cameras from [17].

For the 3D tracking, OptiTrack cameras must be calibrated for the system to know the relative position of each camera in the space. The performance of this calibration requires a specially designed marker tool. This tool is called OptiWand, and it consists of three aligned markers with fixed positions (**Figure 10**).

Figure 10: OptiTrack calibration tool, OptiWand, from [18]

The camera calibration procedure consists of moving the OptiWand along the working space of the set of cameras. As the system knows the spatial configuration of the wand markers, relative positions of the cameras can be computed by using the projections of the wand's markers for several spatial locations within the working space. In general terms, calibration consists on the acquisition of samples at different positions of the wand, and an algorithm that provides the 3D space location of each camera based on those samples (**Figure 11**). These samples must be acquired along the whole volume of the working space, and the number of samples will determine the quality of the calibration. When all desired samples have been acquired, the tracking system software will calculate the best calibration parameters from the available set of samples, and the calibration parameters will be saved into a calibration file.

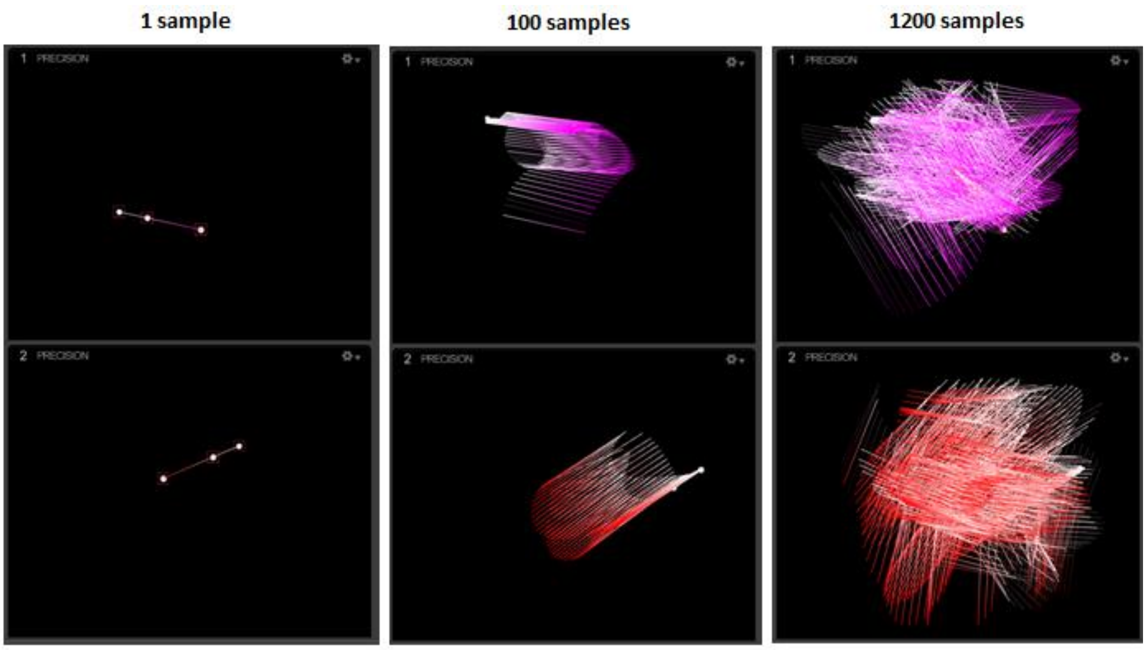

Figure 11: Acquisition of samples for calibration of a two-camera tracking system by moving the OptiWand tool along the field of view of the cameras.

Clearly, a slight variation in the position of any of the cameras composing the tracking system will result the miscalibration of the system, and, as a consequence, an increased error in the tracking performance of the system. If the variation is excessively increased, the system will be unable to track any rigid body due to the extreme distortion (triangulation is unable to calculate a unique solution).

Once the tracking system has been calibrated and a registration with respect to the patient has been obtained, the IGS navigation system is able to show the tools throughout the patient images and to allow the guidance.

1.2.2. COMMUNICATION WITH OPTITRACK OPTICAL TRACKING SYSTEM

Tracking data can be accessed in real time through network streaming support or by using the software API (Application Programming Interface).

- Real-time and recorded data can be streamed over the network for use in other applications. There are several methods available for streaming data over TCP/IP on the network, making data available on the local computer as well as remote network computers.
- An API consists on a set of functions of a software component that allows a programmer to develop software applications [13] and to communicate to other software applications.

During the development of this project the communication has been performed using the Tracking Tools API, which is given as a set of C/C++ function that can be called from a loadable DLL.

2. MOTIVATION AND OBJECTIVES

The camera system that performs the tracking in the IOERT operating room comprises eight OptiTrack cameras in rectangular shape configuration along the ceiling and surrounding the surgical site. This system needs to be calibrated for a correct and reliable performance. However, the calibration process requires very specific conditions: availability of the operating room prior to surgery, removal of instrumentation from field of view, use of calibration tools along the entire room, and cleaning of the operating room after its completion. In many cases, this process may take about 45 min plus extra cleaning time of approximately 20/30 min.

An alternative to calibration every time tracking system is used would be to perform a calibration every certain period of time. However the operating room conditions are unknown to maintain the relationship of position and orientation of the cameras over time. In addition, sometimes during surgery and before its use, the tracking system has suffered unintentional bumps produced by the surgical staff. In some cases, these miscalibrations have not been reported, which could result in a collection of erroneous tracking data. Consequently, for the use of this alternative it is necessary to know the temporal calibration stability and be able to detect accidental camera movements (miscalibrations of the system).

Therefore, the main objectives of this project are:

(1) Determining an optimal method to detect the need for calibration of the tracking system avoiding long delays.

(2) Evaluating the stability of tracking system calibration.

2.1. MISCALIBRATION DETECTION

The first goal of the project is to determine the appropriate method to ensure that the tracking system is correctly calibrated, by detecting if any of the cameras has been deviated from their position during calibration (miscalibration).

The calibration failure detection method must fulfil the following identified requirements:

- Fast: results must be obtained in a short time since the objective is to save that time required for calibration when calibrating is not necessary.
- Easy to perform and minimal prior knowledge required: hospital personnel must be able to perform it following a defined protocol.

2.1.1. APPROACHES TO DETECT MISCALIBRATIONS

Two different approaches have been considered in order to detect miscalibrations within the tracking system: camera projection error, and camera pairs tracking approach.

❖ Camera Projection Error Approach

The OptiTrack tracking is based on projecting the 3D position of reflective markers into the 2D plane of each camera. This projection can be calculated from a 3D location of an optical marker and the known camera plane location from calibration parameters. However, when a camera is miscalibrated, the projected 3D marker into the plane will not match the real obtained projection - camera projection error (**Figure 12**). This approach is based on evaluating camera projection error to distinguish miscalibrated cameras from calibrated ones.

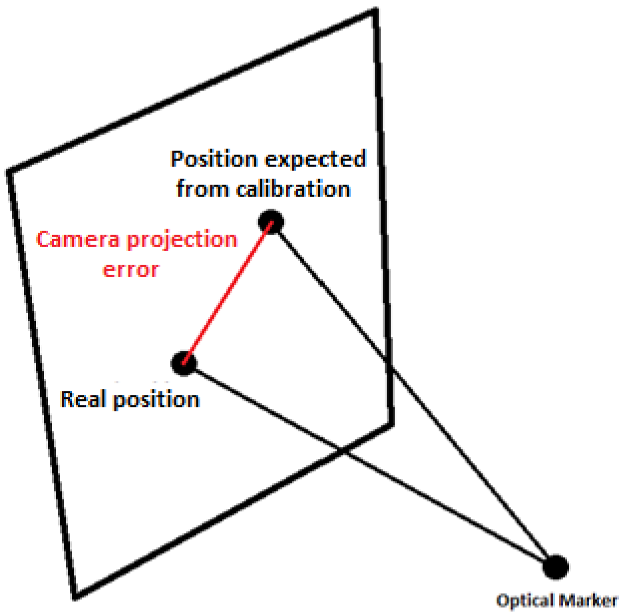

Figure 12: Camera 2D plane where markers are projected. The camera projection error is shown in red.

The evaluation of the camera projection error in order to detect miscalibrated cameras includes the assessment of the mean and standard deviation of the camera projection error.

Regarding the mean value of the camera projection error, it is expected to be above certain threshold value for miscalibrated cameras, and below otherwise. This expected result is based on the assumption that the error originated from the camera deviation was accumulated in the deviated cameras. However, it could take place a compensation of the error between all cameras during the tracking process. This could lead to wrong 3D marker localization and to decrease the projection error along cameras. However, it is expected that the standard deviation of the projection error increases if the 3D marker position is tracked from different locations along space. The expected behaviour for the variability of the error will be a change in the distribution of the camera projection error in all cameras, from a narrow distribution (low standard deviation) to a wider one (high standard deviation) (**Figure 13**).

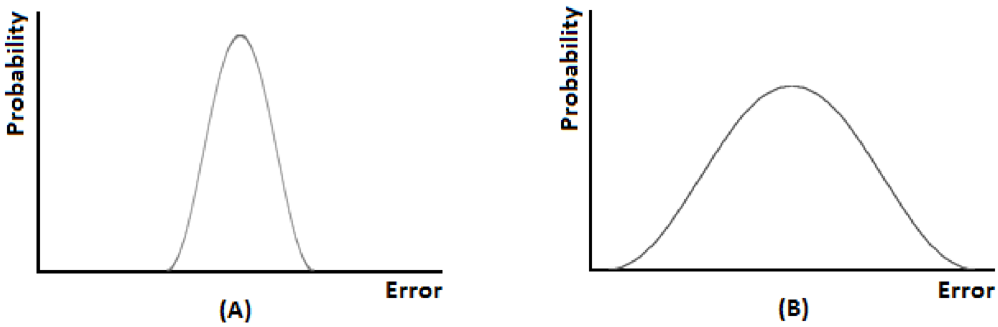

Figure 13: Profiles of distribution for low (A) and high (B) standard deviation.

- Camera Pairs Tracking Approach

The optical tracking system installed in the operating room of the hospital is composed of eight OptiTrack cameras, since a high number of cameras are needed to avoid line-of-sight obstructions during surgery. As the number of cameras composing the tracking system increases, the influence of the miscalibration of a single camera (i.e. the error in the computation of the 3D position of a marker) decreases. Therefore, camera deviations will be more evident to be detected when tracking a marker with a system composed of a lower number of cameras.

Thus, this second approach consists of tracking a single reflective marker using all different camera pairs combinations instead of using the whole set of cameras within the system.

The expected results for this approach will be that miscalibrated cameras could be inferred by determining which cameras belong to those pairs locating the marker in a 3D position more different from the real one (i.e. the 3D position tracked by using all cameras).

When a pair of cameras is used for tracking, a slight deviation of one or both cameras causes a large distortion of the 3D position. If this miscalibration is accentuated, the distortion will increase until the marker will no longer be tracked anymore, since triangulation method will be unable to compute a unique solution. Consequently, it will be crucial to study the behaviour of this 3D distortion as the miscalibration is increased, and to determine the maximum miscalibration one camera is able to suffer before the marker is no longer tracked.

In brief, the two approaches to be assessed in order to determine the optimum methodology for detecting miscalibrations of the optical tracking system are:

i. Studying the camera projection error.
ii. Tracking a marker with all different combinations of camera pairs.

2.2. CALIBRATION TEMPORAL STABILITY ASSESSMENT

The second goal of this project is to study the temporal stability of the system calibration. The assessment of the system stability in time is incredibly important, and will enable to determine the still unknown temporal behaviour of the OptiTrack tracking system. A demonstration of the stability of the calibration will lead to define future protocols for calibration performance, based on calibrating every certain period of time instead of calibrating every time the tracking system is used. Those protocols would be more convenient for health professionals and most importantly, they would allow the hospital to save time and money.

One of the main limitations of this assessment is related with the unknown conditions of the operating room. Sometimes, surgical staff causes deviations in some cameras of the system as a result of the movements of surgical instrumentation. For a correct assessment of the stability, conditions within the operating room must be known in order to avoid external factors to influence on the temporal behaviour of the tracking system. Detecting miscalibrations of the system (objective 1) will be important for a reliable assessment of the temporal stability.

The stability of the calibration quality throughout the entire duration of the experiment can be assessed by analyzing the stability of the tracking information given for an exactly similar scenario.

The expected results of the assessment will be that, if no people access the operating room during the period of time of the experiment, the quality of the calibration must be maintained along the whole duration of the experiment when the scenario to be tracked is stable (objects to be tracked at identical location).

3. MATERIALS

3.1. LIST OF MATERIALS

Tracking System	8 OptiTrack Flex 13 cameras
	2 Stolmen posts
	10 Manfrotto Super Clamps
	2 OptiTrack Flex 3 cameras
	10 USB camera cables
	3 USB hubs
	1 hardware USB key
	Tracking Tools software
	Rigid body
	OptiWand kit (Calibration wand)
Phidget Orientation Sensor	
Visual Studio 2013	
Laptop	

3.2. TRACKING SYSTEM

The experiments have been performed in two different systems:

- The first system is a two-camera (Flex 3) OptiTrack tracking system placed at Laboratorio de Imagen Médica (LIM) in Hospital General Universitario Gregorio Marañón (HGGM) (**Figure 14**).

- The second system is the Intraoperative Radiotherapy Operating Room which belongs to the Oncology Department of the hospital. This operating room, as previously mentioned in the first section, includes an 8-camera (Flex 13) tracking system, and it constitutes the real scenario for IOERT treatments (**Figure 1**).

Due to the low availability of the operating room, the two-camera system of the LIM was needed for the performance of several tests previous to the final experiments, and also as a setup for some experiments in which this two-camera tracking system was sufficient to study certain hypotheses.

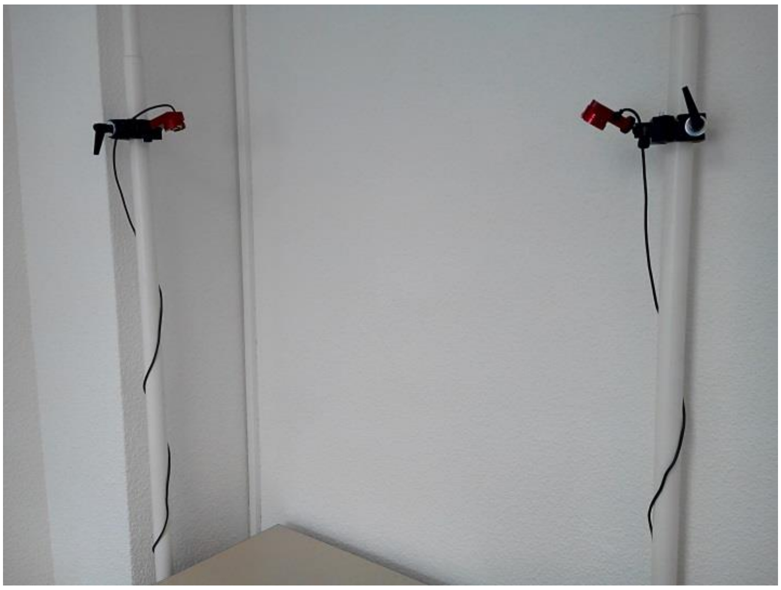

Figure 14: Tracking system composed of two OptiTrack cameras attached to vertical bars (Stolmen posts).

Cameras composing the two-camera tracking system of the first scenario are OptiTrack Flex 3 cameras, while the ones composing the OR tracking system are OptiTrack Flex 13. Comparing both devices, the main difference is the resolution:

- Flex 3 cameras resolution: 640 x 480
- Flex 13 cameras resolution: 1280 x 1024

The Flex 13 cameras cover a large volume within the OR but have high resolution, while low resolution Flex 3 cameras are closer to the rigid bodies to be tracked since the working space is much smaller. Therefore, the effect of this difference in camera resolution is expected to be compensated by the different working space volume of the two sets of cameras.

Regarding fixation of cameras, cameras in both setups were attached by Manfrotto Super Clamps (**Figure 15**). These devices provide a fixed attachment of the cameras either to Stolmen posts (first system) or to metallic horizontal bars of the operating room ceiling (second system).

Figure 15: OptiTrack camera attached to Manfrotto Super Clamp.

With respect to the connection of the hardware with the control computer, the cameras were connected through USB hubs where USB cables coming from the cameras were attached (**Figure 16**).

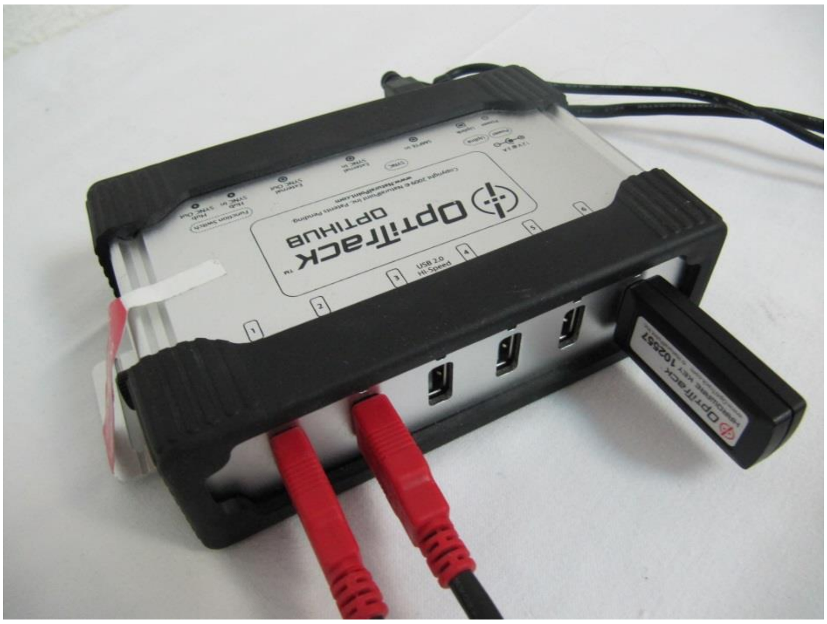

Figure 16: OptiTrack Optihub-2 connected to 2 camera USB cables and USB key containing the software license.

The Tracking Tools software allows the control of the camera calibration parameters and the real-time visualization of the 3D tracking and cameras field of view (FOV) (**Figure 17**). For using this software a license is needed, which is contained in a hardware USB key that is connected to the USB hub.

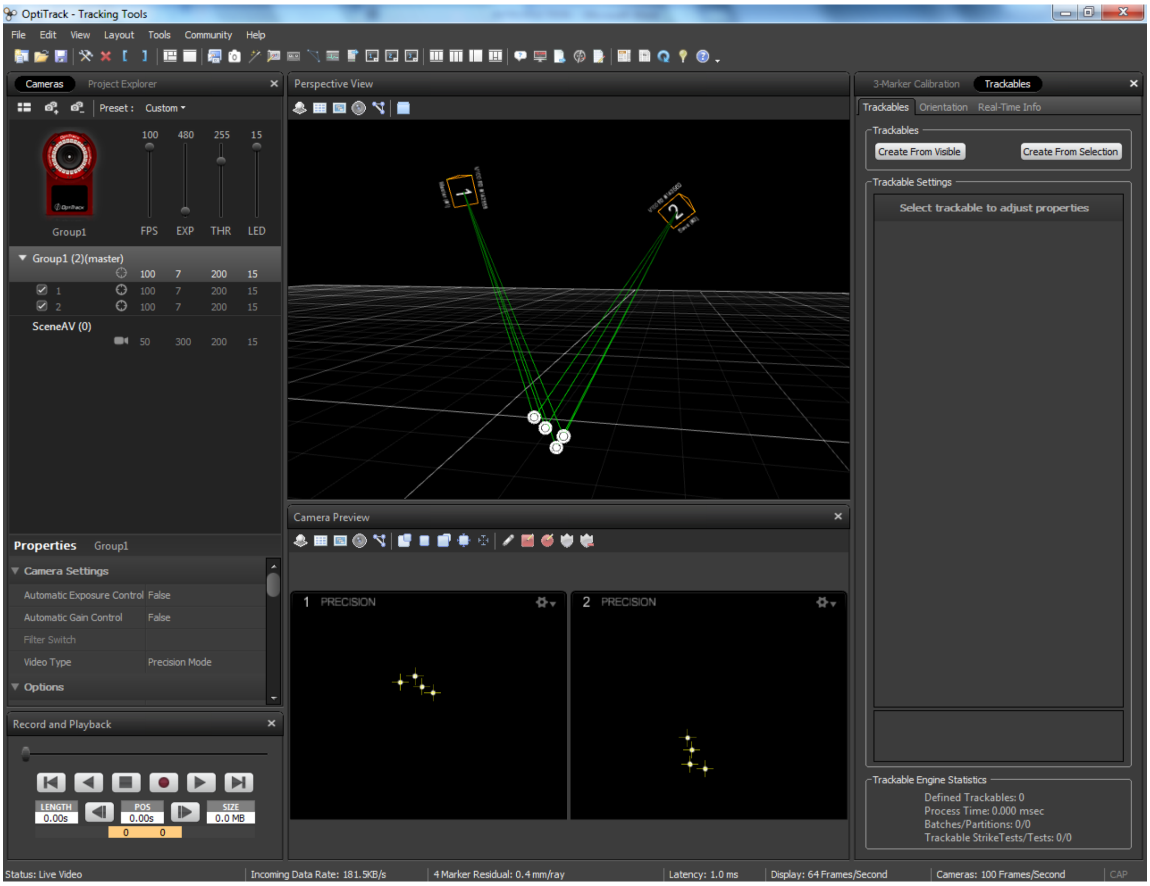

Figure 17: Capture of the Tracking Tools software when tracking a 4-marker rigid body with a two-camera tracking system.

Moreover, for the performance of the calibration the specially designed marker tool OptiWand is necessary. The OptiWand tool used consists of three aligned markers with fixed positions within a 25 cm length (**Figure 10**).

Finally, for the performance of the experiments a tool composed of 4 markers was used - the NDI Polaris Pointer (**Figure 8.a**). Some experiments required a lower number of markers and, therefore, some markers were detached from this rigid body.

3.3. PHIDGET ORIENTATION SENSOR

To quantify miscalibration of a single camera, a sensor was attached to the back of the camera in order to measure its angular orientation. The sensor used was the PhidgetSpatial Precision 3/3/3 (**Figure 18**). This sensor combines the functionality of a 3-axis compass, a 3-axis gyroscope, and a 3-axis accelerometer, and provides high resolution measurements [14].

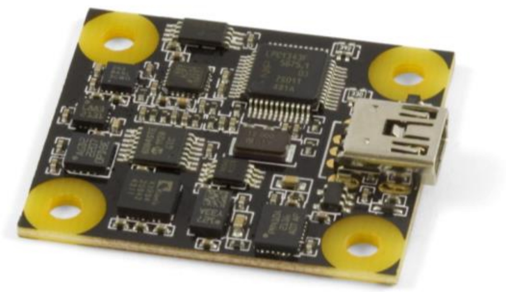

Figure 18: PhidgetSpatial Precision 3/3/3 orientation sensor [19].

This sensor was attached to one camera (**Figure 19**) and connected via USB to the computer where the acquired orientation data was saved. Three measurements of orientation were provided, one per method of sensing: compass, gyroscope, and accelerometer.

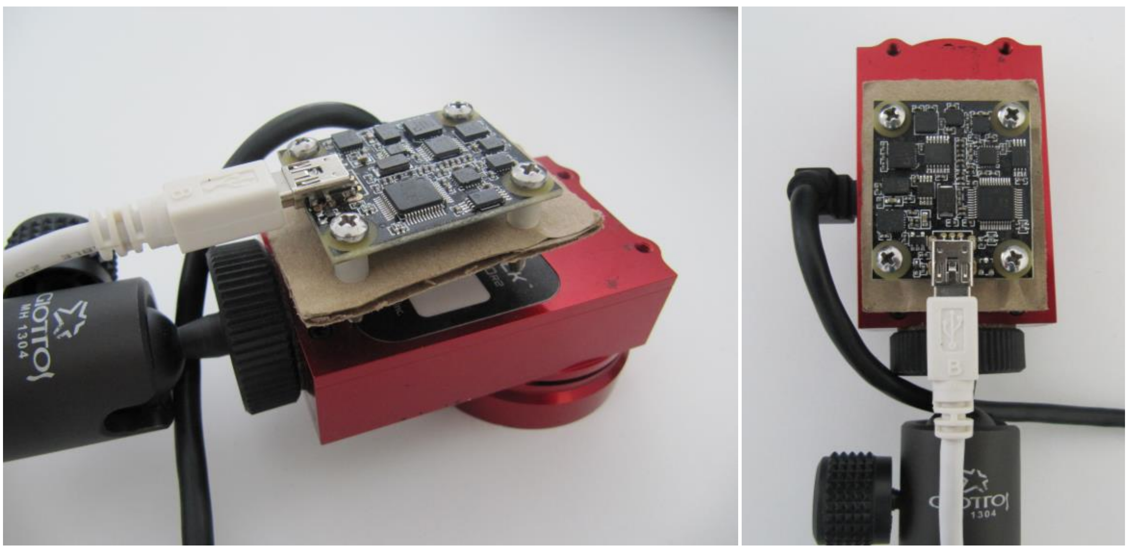

Figure 19: Phidget orientation sensor attached to an OptiTrack camera.

4. METHODS

This section describes the hardware and software interconnection in order to carry out the described experiments and data acquisition.

4.1. DATA ACQUISITION

Communication with the tracking system was established by using the Tracking Tools API, which allowed an optimal control of the tracking system cameras and parameters adapting the different experiments to specific objectives. This API consists of a set of functions that allows users to develop software applications for the control of a large number of features of the tracking system.

Different applications were developed for the control of the tracking system and for the acquisition of tracking information in each of the different experiments performed during the project. These applications are:

- **Camera Projection Error Application:** Its objective is to compute the camera projection error of each camera. It obtains the real 2D positions of the markers within camera planes. Then, the application calculates the 3D positions of the markers expected from the calibration, and projects these positions into each camera plane in order to find the calibrated 2D positions. Finally, the distance between 2D projections (camera projection error) is computed and saved into a ".csv" file, enabling a posterior data analysis. This application acquires 10000 samples of the camera projection error per marker and per camera.

- **Alternative Tracking Application:** Its purpose is to obtain the 3D positions of a single marker given by all possible combinations of camera pairs within the tracking system. It uses 2 out of the total number of cameras each time for the tracking of the marker by setting the parameters of the other cameras in such a way that no markers can be detected by them (maximum threshold and minimum exposure). This application acquires 1000 samples of the 3D position of the marker per camera pair.

- **<u>Temporal Stability Application</u>:** This application was developed to run during 5 consecutive days in order to evaluate the stability of an initial calibration of the system. First, the calibration file of that calibration whose stability wants to be evaluated is loaded. Then, every 4 hours the application: acquires the 3D position of a marker using all available cameras in the operating room, and also runs the Alternative Tracking Application in order to track the marker using camera pairs. All tracking information is saved into a ".csv" file.

Moreover, for the testing of the applications it was necessary to install and connect the system to the computer since the use of the real API functions require direct communication with the OptiTrack cameras.

In order to enable the testing of the application without the connection to the tracking system, a new software library was implemented to work as a 'fake' API. The development of that library required the analysis of the whole set of functions included in the real API. The objective was to include functions with the same name and inputs as the real API ones, but returning specified outputs whose values indicate if the functions have been called correctly or not. This fake API contained a total of 41 functions providing output values which are disclosed in the documentation for ease of use. Therefore, the implemented library will serve to test applications before they are used and to avoid future errors.

Finally, another application was generated to acquire the provided angular information given by the Phidget orientation sensor (*Sensor Application*). The connection with the sensor was established through the PLUS library, which is an open-source software package containing applications for real-time data acquisition, processing, streaming and calibration [15]. On the other hand, the acquisition of angular positions was made using OpenIGTLink, which is an open network protocol for communications in the image-guided therapy environment [16]. The *Sensor Application* was coded in Python programming language for connection, data acquisition, and saving of the angular displacements (with respect to initial position of the camera) into a ".csv" file.

4.2. MISCALIBRATION DETECTION

The two approaches to determine the optimum methodology for detecting miscalibrations and to be tested during these calibration failure detection experiments are:

(1) Analysing the camera projection error of cameras in the system.

(2) Alternative tracking with all possible pair combinations of cameras composing the tracking system.

4.2.1. CAMERA PROJECTION ERROR APPROACH

PILOT EXPERIMENT	
Materials	- Rigid body of 4 markers
	- 2 Optitrack cameras
	- Optiwand calibration tool
Methodology	1. Calibration of cameras
	2. Acquisition of tracking data
	3. Computation of camera projection error
	4. Statistical analysis of the data

A **pilot experiment** was performed in order to test the feasibility of *camera projection error approach* based on detecting miscalibrations by analysing camera projection error of different cameras. The system used is the tracking system composed of two OptiTrack Flex 3 cameras, which was firstly calibrated following the calibration protocol by moving the OptiWand tool within the working space of the cameras.

Camera Projection Error Application was used to compute the projection errors of each camera and marker, the absolute distance in the 2D plane of the cameras between the current markers position and the expected position of the markers from calibration.

Two tests were performed in this experiment using a four-marker rigid body:

- **Both cameras calibrated** and rigid body moved following a curved trajectory within the field of view.

- **One camera (Camera 2) slightly deviated** and rigid body moved following a curved trajectory within the field of view.

Finally, a statistical analysis of the data was done. The distributions of the error for every camera and marker were obtained for every case.

CAMERA PROJECTION ERROR EXPERIMENT	
Materials	- Rigid body of 4 markers
	- 8 Optitrack cameras
	- Optiwand calibration tool
Methodology	1. Calibration of cameras
	2. Acquisition of tracking data
	3. Computation of camera projection error
	4. Statistical analysis of the data

Based on the pilot experiment results, **Camera Projection Error experiment** was performed as a final experiment to assess more extensively the feasibility of using the camera projection error as the main factor to determine the calibration state of the tracking system. For this experiment the system composed by eight OptiTrack Flex 13 cameras was used, and a high quality calibration was performed using OptiWand tool.

Four different tests were performed using a four-marker rigid body, repeating each of them 25 times. For each of the tests the *Camera Projection Error Application* was used for data acquisition. The different tests were:

- **Cameras calibrated** and rigid body moved following a curved trajectory within the field of view.
- **One miscalibrated camera** and rigid body moved following a different curved trajectory within the field of view.
- **Two miscalibrated cameras** and rigid body moved following a different curved trajectory within the field of view.
- **Three miscalibrated cameras** and rigid body moved following a different curved trajectory within the field of view.

Finally, all information was statistically analysed by evaluating camera projection error distribution: the mean value and the variability of the error. The variability refers to how spread out the camera projection error distribution is. Two parameters used to describe variability were computed from the distribution and studied. The parameters studied were:

- Standard Deviation (SD): amount of variation or dispersion of the set of values.
- Interquartile Range (IQR): the range of the middle 50% of the samples in the distribution.

4.2.2. CAMERA PAIRS TRACKING APPROACH

CAMERA PAIRS TRACKING EXPERIMENT	
Materials	- Rigid body of 1 marker
	- 8 Optitrack cameras
	- Optiwand calibration tool
Methodology	1. Calibration of cameras
	2. Acquisition of tracking data
	3. Statistical analysis of the data

Camera pairs tracking experiment was carried out in order to assess the possibility of detecting miscalibrations within the tracking system by tracking markers with all possible combinations of camera pairs (*camera pairs tracking approach*). For this experiment the system composed by eight OptiTrack Flex 13 cameras was used too, and a high quality calibration was performed using OptiWand tool.

A rigid body composed of just one marker was used in a static similar position all over the experiment. The marker was tracked by all possible pair combination of cameras using the *Alternative Tracking Application* developed. Thanks to this application the tracking information was limited to just 2 out of 8 cameras each time by deactivating those cameras which do not belong to the given pair.

Five repetitions were performed for each of the following tests where miscalibrated cameras were chosen randomly from the whole set of available cameras:

- **Cameras calibrated** and marker fixed.
- **One camera miscalibrated (Camera 3)** and marker fixed.
- **Two cameras miscalibrated (Cameras 3 and 8)** and marker fixed.

- **Three cameras miscalibrated (Cameras 1, 3, and 8)** and marker fixed.
- **Four cameras miscalibrated (Cameras 1, 3, 4, and 8)** and marker fixed.

Finally, the analysis of the data consisted on grouping the tracking information (3D position of the marker) for each combination of the eight cameras (a total of 28 pairs). Moreover, it was necessary to separate those erroneous 3D positions representing that pairs of cameras were not able to track the marker.

MISCALIBRATION QUANTIFICATION EXPERIMENT	
Materials	- Rigid body of 1 marker
	- 2 Optitrack cameras
	- Orientation sensor
	- Optiwand calibration tool
Methodology	**1.** Attachment of sensor to a camera
	2. Calibration of cameras
	3. Acquisition of tracking data
	4. Statistical analysis of the data

The purpose of **Miscalibration Quantification experiment** is to evaluate quantitatively the maximum miscalibration one camera within a 2-camera tracking system is able to suffer before the tracking ability of that camera pair is lost (no marker tracked).

With this objective in mind, an orientation sensor was attached to the back of a camera enabling the accurate quantification of the miscalibration (**Figure 19**). Since the camera may be miscalibrated during the attachment of the sensor, this arrangement must be prepared before the camera calibration. Then, the first step was to attach the sensor to the back of camera number 2. Later, the calibration of the two-camera tracking system was performed using the OptiWand tool.

A rigid body containing just one reflective marker was used in a static and fixed position throughout the experiment.

The acquisition of data was done independently for the tracking system and the sensor. Five repetitions were performed for each different calibration state of the system. For each repetition tracking information containing the 3D position of the marker and orientation information provided by the sensor were saved into two different files using *Alternative Tracking Application* and *Sensor Application,* respectively.

The experiment was based on rotating the camera 2 (with the orientation sensor attached) several times in the same direction and homogeneously until the marker is no longer tracked (**Figure 20**). It was possible to move the camera manually four times before it stopped tracking the marker.

Figure 20: Movement of camera 2 during miscalibration quantification experiment.

Five data acquisitions were performed for each of the different calibration states of the system:

- **Both cameras calibrated** and marker fixed.
- **Camera 2 miscalibrated (movement 1)** and marker fixed.
- **Camera 2 miscalibrated (movement 2)** and marker fixed.
- **Camera 2 miscalibrated (movement 3)** and marker fixed.
- **Camera 2 miscalibrated (movement 4)** and marker fixed.

For the analysis of the data, the error distributions in both 3D positions of the marker and orientation of camera 2 were computed.

4.3. CALIBRATION TEMPORAL STABILITY ASSESSMENT

The assessment of the calibration quality in this experiment was performed by analyzing the stability of the tracking information given for an exactly similar scenario. The objective of this experiment is to demonstrate that the quality of calibration is maintained along the whole duration of the experiment when the scenario to be tracked is stable.

A key issue in this experiment is to avoid variation in the operating room in order to study just the temporal stability without any external factors such as possible miscalibrations as a result of bumps during surgery. Therefore, the experiment was specifically scheduled in a period of time when the operating room was not used. Although, no surgical procedures were planned during those 5 days, all the necessary steps were taken to avoid people entering into the experiment scenario.

Firstly, the calibration of the tracking system of the operating room was performed. This calibration was the only one performed throughout the experiment, and therefore the one whose stability has been studied.

Next, a developed application (*Temporal Stability Application*) was initiated for the acquisition of data. The function of the application is to acquire both the 3D position using 8 cameras and the 3D position using all 28 possible combinations of camera pairs every 4 hours and during 5 whole days, saving all tracking information into ".csv" files.

Finally, all tracking data files were collected and analyzed by grouping tracking information depending on which cameras were used for its acquisition in order to obtain the independent temporal behavior for each subset of cameras (individual camera pairs or whole set of eight cameras).

4.4. ANALYSIS OF RESULTS

All data obtained from the different performed experiments was saved into ".csv" files and then analyzed using R, a software environment for statistical computing and graphics.

5. RESULTS AND DISCUSSION

This section describes the results of the performed experiments. First, the results of the experiments related with the detection of camera miscalibrations are shown. Later, a presentation of the results regarding stability of the calibration is done. To conclude, a scheme of the final methodology proposed is presented.

5.1. MISCALIBRATION DETECTION

5.1.1. CAMERA PROJECTION ERROR APPROACH

- **Pilot Experiment**

The purpose of this experiment was to assess the feasibility of detecting miscalibrations in the tracking system (i.e. miscalibrated cameras) by using the camera projection error. The expected results for the tracking data when a camera is miscalibrated were an increased mean camera projection error associated with this camera in comparison with the projection error of correctly calibrated cameras.

Figures 21 and **22** show the camera projection error distribution for each marker in the plane of each of the cameras, in other words, the difference (distance within the plane) between the 2D projections of the real and the actual 3D positions. In both graphs, the data has been grouped for each individual marker and camera.

In **figure 21**, where both cameras were calibrated, the mean camera projection error is within the same range for both cameras (1 and 2). On the other hand, **figure 22** shows the results when one camera (1) has been miscalibrated and it is observed how the mean camera projection error remains within the same range than in the calibrated case. When comparing both plots, there is not an increase in the mean camera projection error values when the system was miscalibrated. The only visible difference is an increased interquartile range (IQR), indicating an increase in the variability of the camera projection error (in both cameras) as the system was miscalibrated.

A possible explanation to the fact that both cameras in **figure 22** present similar error values, while just one of them (camera number 2) was miscalibrated, may be that a compensation was produced between both cameras.

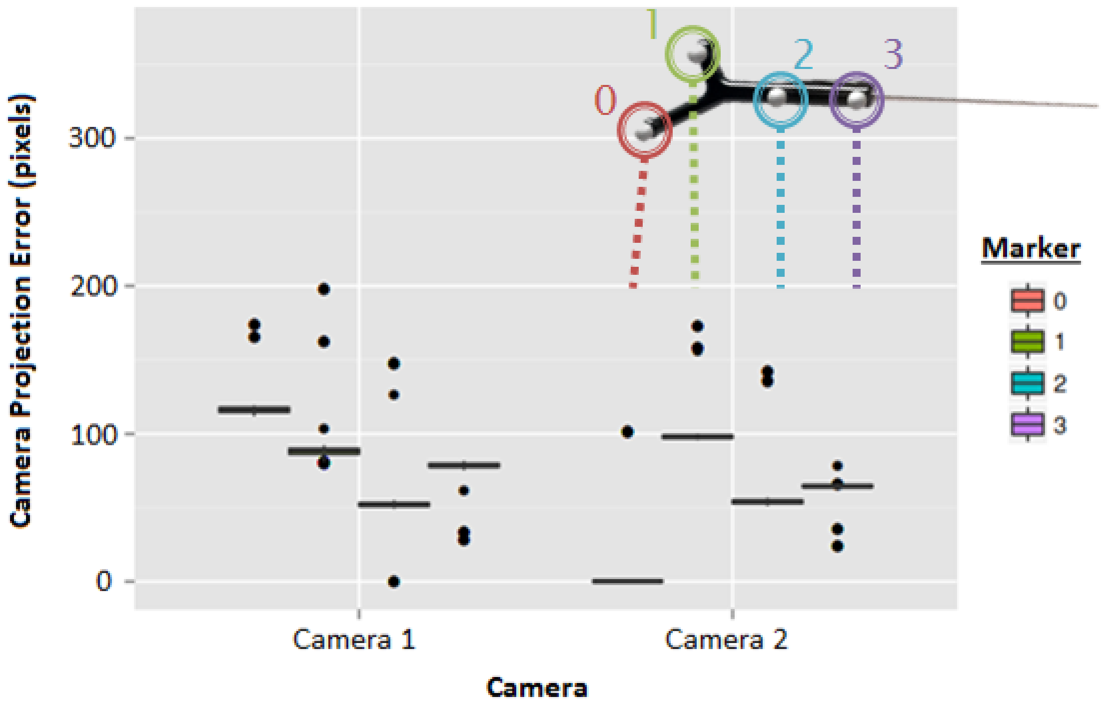

Figure 21: Camera projection error in pixels for two calibrated cameras and acquiring tracking data for a moving rigid body.

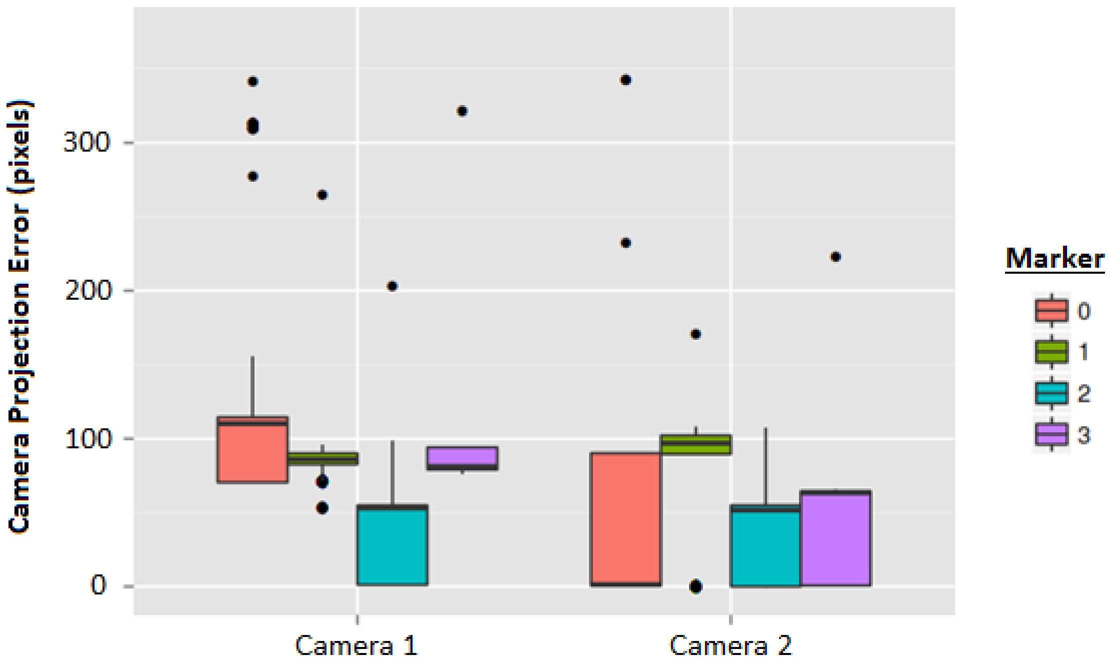

Figure 22: Camera projection error in pixels for camera 2 miscalibrated and acquiring tracking data for a moving rigid body.

Two main limitations were found when using this methodology:

- Since the rigid body was being moved within the field of view during the acquisition, it was necessary to maintain all markers of the rigid body visible for both cameras during the whole tracking period in order to avoid erroneous data in the results.
- Regarding the camera deviation, due to the low number of cameras composing the system an excessive movement of the camera will affect tracking ability. If the tracking ability of the system is lost, the rigid body will not be tracked anymore. If this happens, it will be necessary to repeat the experiment.

According to the results of this experiment, the expected increase in the mean camera projection error as the system was miscalibrated was not fulfilled. Moreover, the change in variability of the camera projection error seems to be a clear indicative of the system miscalibration, but further study must be done.

- ❖ **Camera Projection Error Experiment**

This second experiment was aimed at studying more extensively the feasibility of the camera projection error distribution as the key factor to determine if a system is miscalibrated or not. The tracking of a moving rigid body was performed using eight cameras, and the expected results were an increased standard deviation of the error as a result of introducing miscalibrations into the system (miscalibration of several random cameras).

Figure 23 represents the standard deviation of the camera projection error and **figure 24** shows the density plot of the standard deviation for the different cases under study. Although the growth is higher when first two cameras were miscalibrated than during the movement of the third camera, in both graphs it is noticeable an increasing trend of standard deviation as the number of miscalibrated cameras increases. Therefore, results indicate that the variability of the camera projection error, when tracking a moving rigid body during 25 repetitions, can be used to estimate the calibration state of the system.

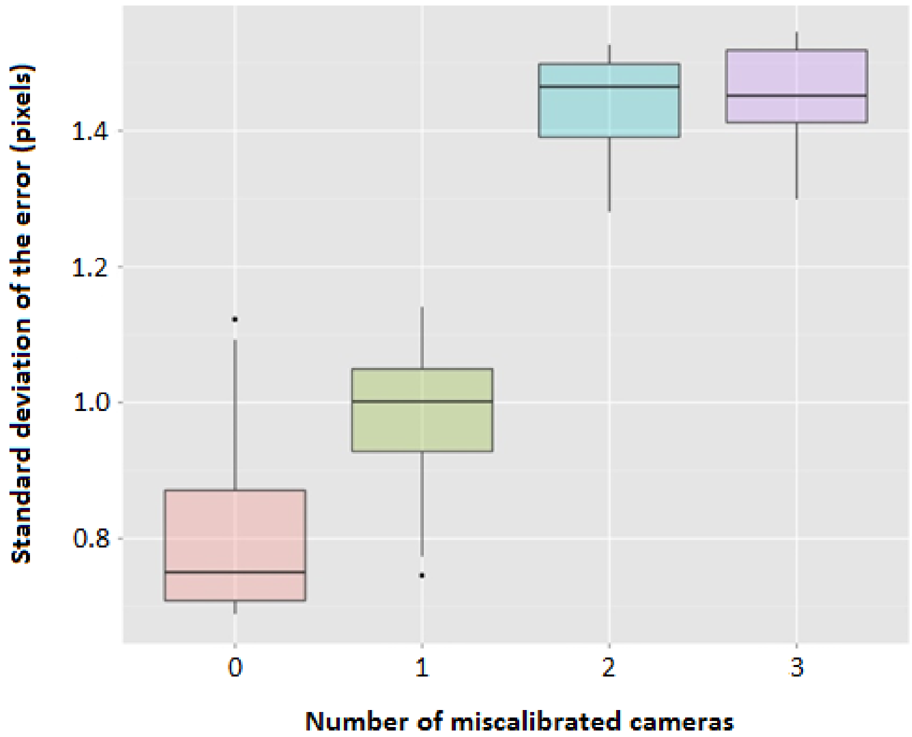

Figure 23: Boxplot of the standard deviation (SD) of the camera projection error for 25 repetitions of each case. Four cases: all cameras calibrated, 1 camera, 2 cameras, and 3 cameras miscalibrated.

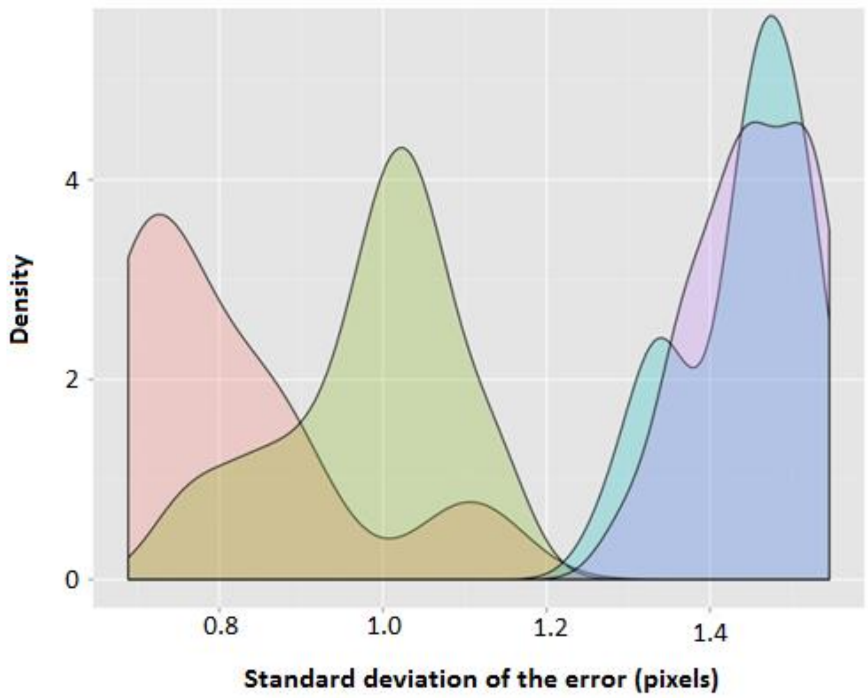

Figure 24: Density plot of the standard deviation (SD) of the camera projection error for 25 repetitions of each case. Four cases: all cameras calibrated, 1 camera, 2 cameras, and 3 cameras miscalibrated.

Another important parameter studied was the interquartile range (IQR), which provides also information about the statistical dispersion of data. Although both standard deviation and interquartile range represent the variability or statistical dispersion, the IQR is more resistant to outliers than standard deviation which is really sensitive to them. **Figure 25** shows the IQR values for the four different tests performed (25 repetitions each). Although an increase of the variability with miscalibration is evident, the variation when just one camera was miscalibrated is not so prominent in comparison with standard deviation. Thus, detecting one miscalibrated camera will be more complicated using IQR than when using SD.

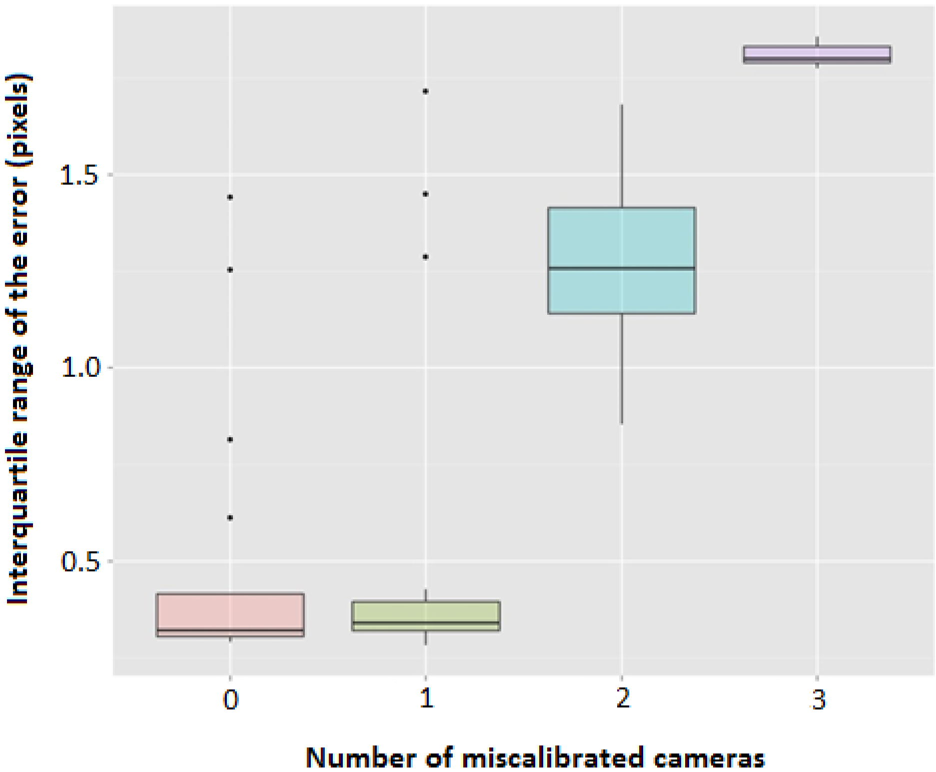

Figure 25: Boxplot of the interquartile range (IQR) of the camera projection error. Four cases: all cameras calibrated, 1 camera, 2 cameras, and 3 cameras miscalibrated.

Results shown in **figures 23**, **24**, and **25** were obtained from the data acquired in 25 repetitions for each of the different cases under study. In order to assess the behavior of the standard deviation for individual repetitions of the tests, tracking information must be analyzed for each repetition.

Figure 26 shows the standard deviation of 2D projection error for each individual repetition and calibration scenario. It can be clearly seen than some repetitions within the first case (all cameras calibrated) presented higher value of standard deviation than repetitions of other cases, while there is an increasing trend of the standard deviation when results from multiple repetitions are averaged.

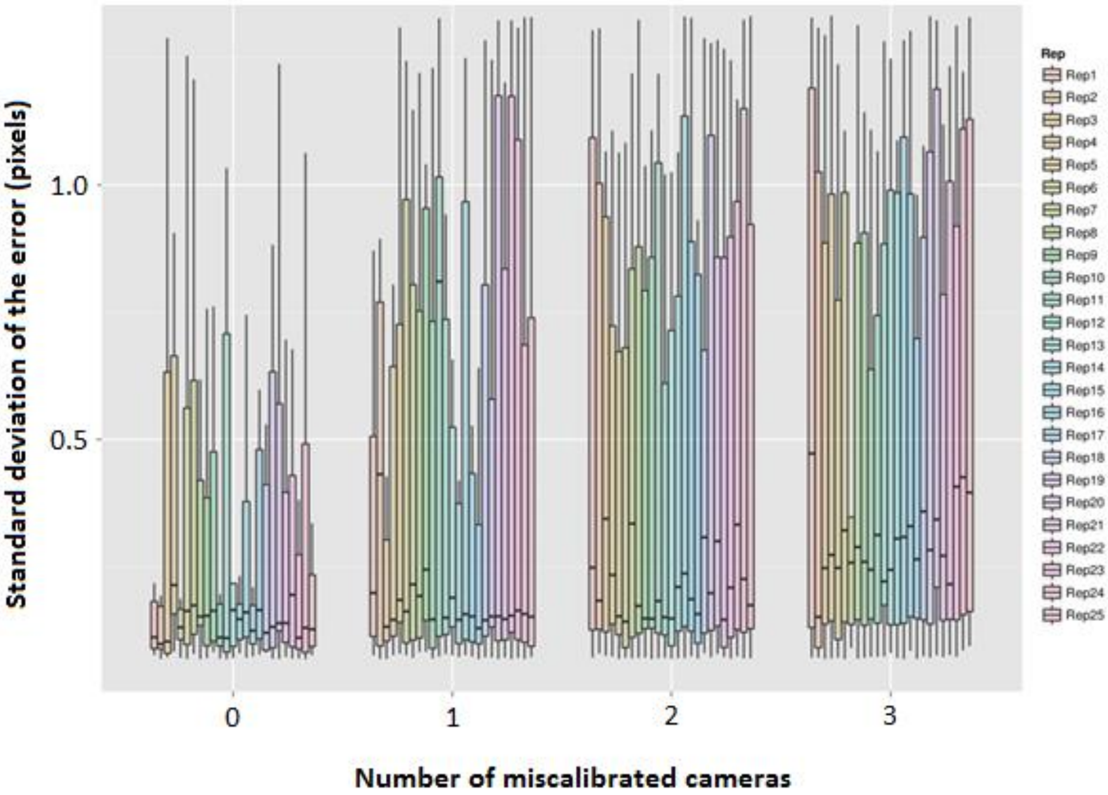

Figure 26: Boxplot of the standard deviation of the camera projection error per repetition. Four cases: all cameras calibrated, 1 camera, 2 cameras, and 3 cameras miscalibrated.

Two main limitations were identified in the methodology of this experiment:

- As in the pilot experiment, since the rigid body was being moved along the working space of the cameras, the movements must be precisely controlled to ensure the detection of the marker during the tracking in order to avoid erroneous data which may lead to the misunderstanding of results.
- By acquiring data of just one repetition of the experiment, the state of the calibration of the tracking system cannot be ensured. For this experiment to provide trustful results the acquisition of several repetitions is necessary.

Finally, attending to the results of this experiment, the variability has been proven to be the key factor to assess the calibration state of a system. However, miscalibration detection following this methodology requires the acquisition of large amount of repetitions to obtain sufficiently reliable results and the requirement of being a fast methodology is not fulfilled. Moreover, by assessing the variability of the error miscalibrated cameras cannot be identified due to compensation between cameras.

5.1.2. CAMERA PAIRS TRACKING APPROACH

❖ **Camera Pairs Tracking Experiment**

The goal of this experiment was to assess the possibility of determining the cameras out of calibration within the tracking system by tracking markers with all possible combinations of camera pairs (*camera pairs tracking approach*). For this evaluation one static marker was tracked with the eight camera system. The expected results were correct 3D positions of the marker when tracked by calibrated pairs of cameras, and erroneous positions for those pairs containing miscalibrated cameras. In this second case, erroneous results may appear in two different ways:

(1) The system is incapable of tracking the marker due to the distortion caused by the deviation of cameras, and no 3D position is provided.

(2) The system is capable of tracking the marker, but the provided 3D position is different from the calibrated position of the marker.

Figure 27 represents the result of tracking the marker for each combination of cameras during just one repetition. A blue square is shown if the marker was tracked by each specific pair of cameras and red otherwise. This plot has been done by grouping the tracking information studying which camera pair combinations produced non-valid 3D positions, which means they were unable to track the marker. These results show that those combinations of cameras containing miscalibrated cameras were the only pairs presenting wrong tracking of the marker.

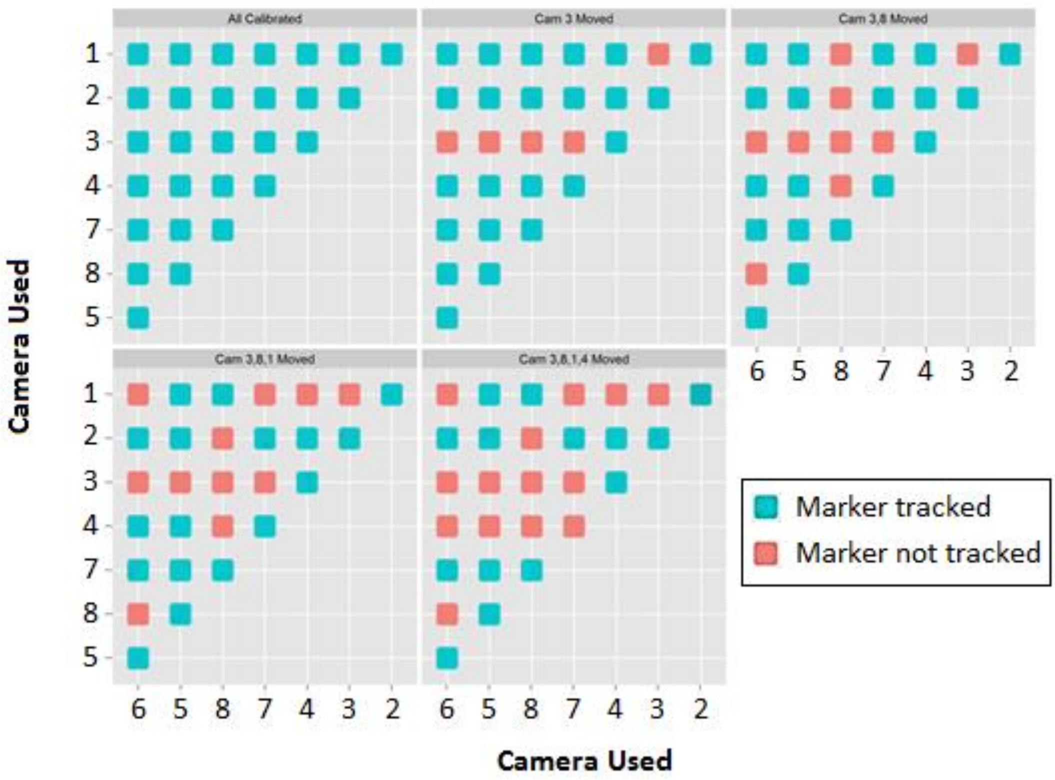

Figure 27: Representation of the tracking of one marker for each possible combination of cameras during one repetition for different calibration states of the system.

In addition, in order to assess the reproducibility of this methodology, the results for five repetitions are shown in **figure 28**. This graphical representation organizes in five different columns the results of each individual repetition performed. The obtained results were similar for all five independent repetitions, indicating a considerable reproducibility of the results. The demonstrated reproducibility enables to obtain reliable results in just one repetition when using this methodology.

However, not all system miscalibrations can be detected by evaluating the ability of the system to track or not the marker, since the deviation suffered by a miscalibrated camera may be sufficiently small for the pair of cameras containing that miscalibration to continue tracking the marker. Therefore, in order to perform a complete assessment of the calibration state of the system, the methodology to follow must be able to detect both slight and severe miscalibrations of the system.

Figure 28: Representation of the tracking of one marker for each possible combination of cameras during every repetition for five different calibration states of the system.

In order to detect slight miscalibrations of the tracking system, marker 3D position distortion must be evaluated in detail. **Figures 29**, **30** and **31** show the position of the tracked marked along each dimension of space (x, y and z). A colour scale is used in the representation for an improved visualization of the differences in the 3D positions provided by the different camera pairs. The 3D positions with coordinates (x, y, z) = (0, 0, 0) corresponds to those cases where the marker was not tracked by the system.

Results show larger distortion in the marker 3D position for those pairs containing miscalibrated cameras, while calibrated pairs of cameras had small or no distortion. Consequently if an appropriate threshold is set indicating the maximum distortion that the 3D position can suffer for the tracking being still considered correct it will be possible to determine with the desired accuracy miscalibrated cameras (miscalibrations of the system). This threshold value will depend on the number of cameras composing the system.

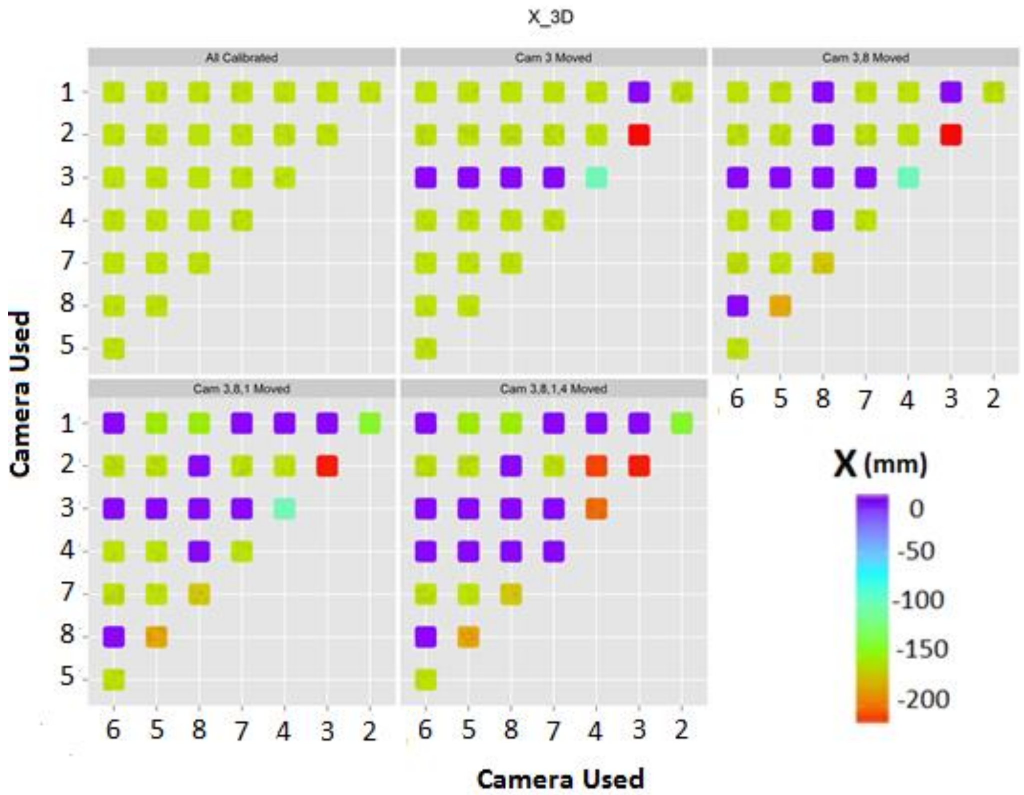

Figure 29: Representation of the x coordinate of the 3D position of a single marker for each possible combination of cameras.

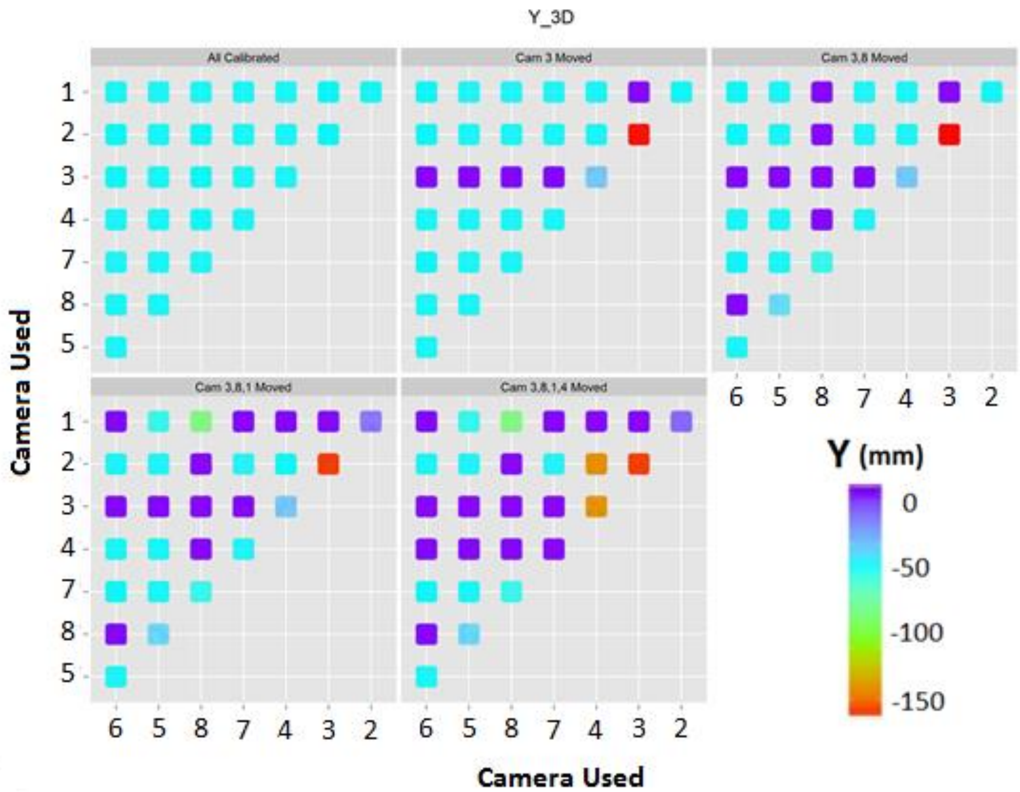

Figure 30: Representation of the y coordinate of the 3D position of a single marker for each possible combination of cameras.

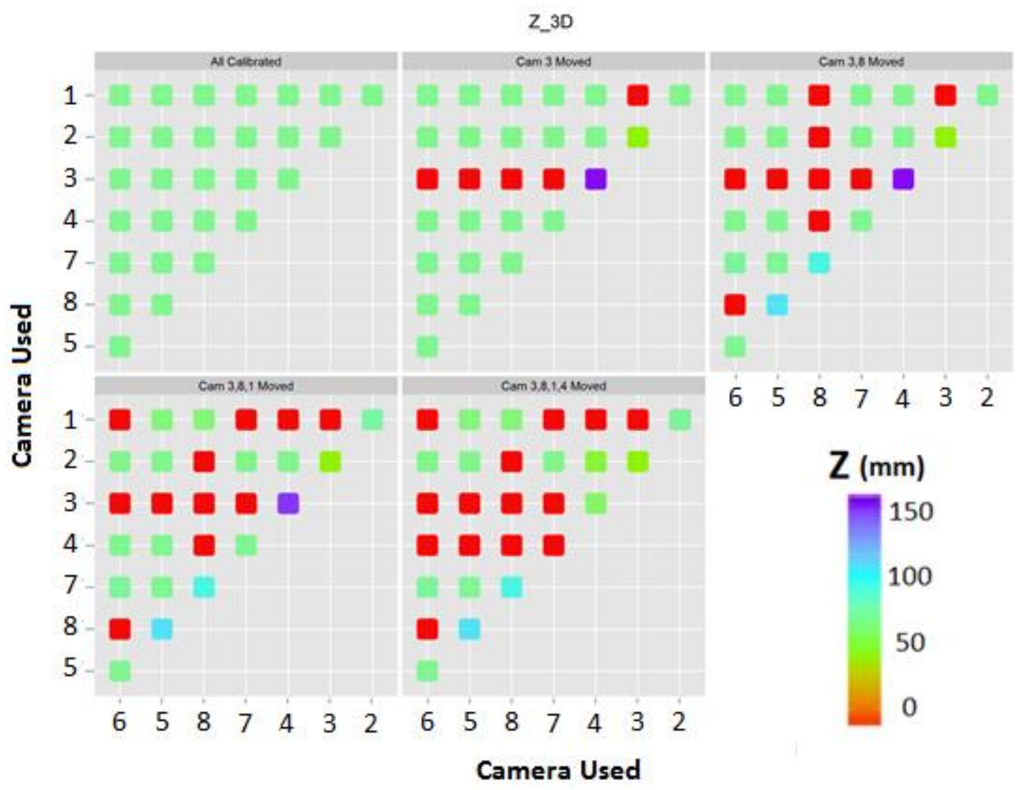

Figure 31: Representation of the z coordinate of the 3D position of a single marker for each possible combination of cameras.

One limitation was identified for the methodology followed in the experiment:

- Problems arise when there is no line-of-sight between the marker and any of the cameras because in this case, as no marker is tracked, this method will determine that the blocked camera is a miscalibrated camera. Therefore, a requisite for this method will be that the marker is contained within the FOV of all cameras of the tracking system.

Finally, the results of the camera pairs tracking experiment reveal the good performance in the assessment of the calibration state of the system of the methodology of camera pairs tracking approach, which is based on tracking a single and static marker with all possible combinations of cameras pairs. This methodology provides reliable results in a short period of time since just one repetition is enough to detect miscalibrations. Considerably large deviations of cameras are instantly identified, while slighter distortions require the predefinition of a threshold for the maximum tolerance of the system to 3D tracking error.

- **Miscalibration Quantification Experiment**

The purpose of this experiment, also related with the *camera pairs tracking approach,* was to quantify the maximum amount of distortion in the calibration position that can be suffered by a camera within a two-camera tracking system before losing its tracking ability (marker not tracked by the system). The information provided by the results of this experiment will be useful to estimate the accuracy of the miscalibration detection in the methodology proposed in this approach.

To perform this assessment several deviations in the orientation of one of the cameras were caused, acquiring tracking information after each of these movements until the instant when no marker was tracked by the system. Four movements were performed, and the orientation variation on the camera was measured using an orientation sensor. The expected behavior of the system as it is miscalibrated was continuous increased distortion of the 3D position of the marker, until certain value from which the marker will be no longer tracked.

A key aspect is to analyze the quality of the deviations produced on the cameras in order to check if the overall displacement was approximately uniform and no large differences existed between them, the desired situation will be four similar movements (homogeneous displacement).

Figure 32 is a graphical representation of the difference in 3D position with respect to the calibrated position of the marker (y axis) versus the angular displacement of the camera (x axis). The reference in this graph for both angular displacement and 3D position is the angular displacement and the 3D position obtained when the system was calibrated. The fourth introduced miscalibration is not shown in the graph since no valid marker position was provided, no marker was tracked. It can be observed the correlated increase of the distortion with the increase in the angular deviation of the camera. It is observed that errors in 3D position of an approximate maximum value of 3 millimeters can appear before the system loses the tracking ability.

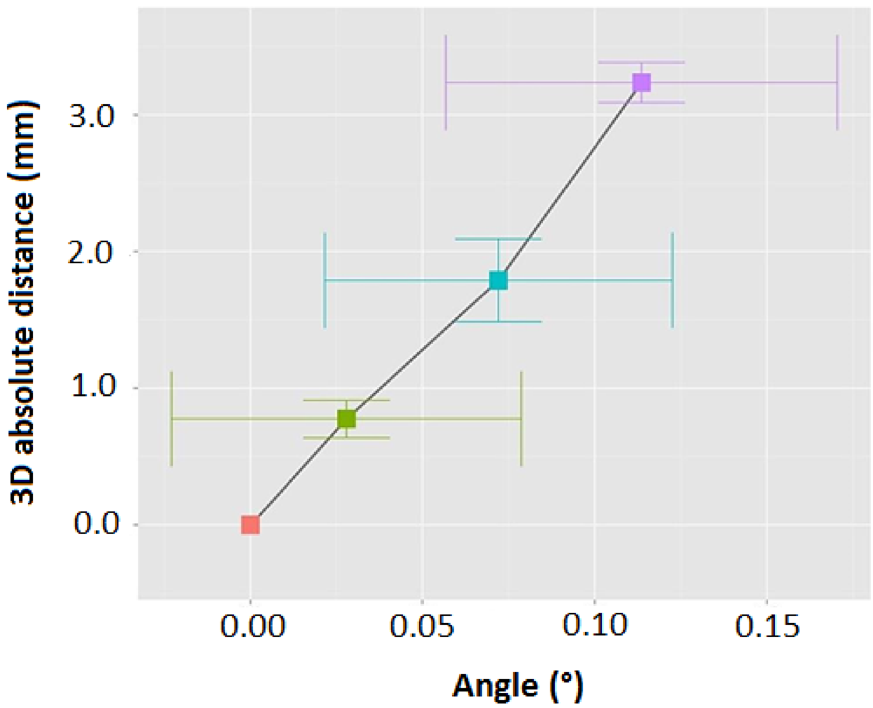

Figure 32: Difference in 3D position of the marker, with respect to the reference initial location, for four different orientations of camera number 2.

In addition, a table containing the angular position of the camera after each movement and the associated error is shown below (**Figure 33**). From this data it can be stated that the four movements produced have increased homogeneously the angular deviation of the camera. The difference in angular position between successive deviations was approximately 0.04 - 0.05°, which was lower than expected taking into account that these successive miscalibrations of the camera were performed manually.

EXPERIMENT	CAMERA ANGLE (°)	MARKER TRACKED
Both cameras calibrated	0.00 ± 0.00	Yes
After movement 1	0.03 ± 0.09	Yes
After movement 2	0.07 ± 0.09	Yes
After movement 3	0.12 ± 0.10	Yes
After movement 4	0.16 ± 0.09	No

Figure 33: Change in orientation of camera 2 after each of the four movements in degrees with respect to initial position and the associated error.

Figure 34 shows if a marker was detected by the system (blue) or not (red) for each of the five different calibration states, for each of the five repetitions per case, and for each of the 1000 samples per repetition. Different rows correspond to different calibration states of the camera, while the different columns show the data for all five different repetitions. Results show that the marker was not tracked just after the fourth movement, where not a single sample provided a 3D position of the marker since the triangulation method was unable to generate a unique solution.

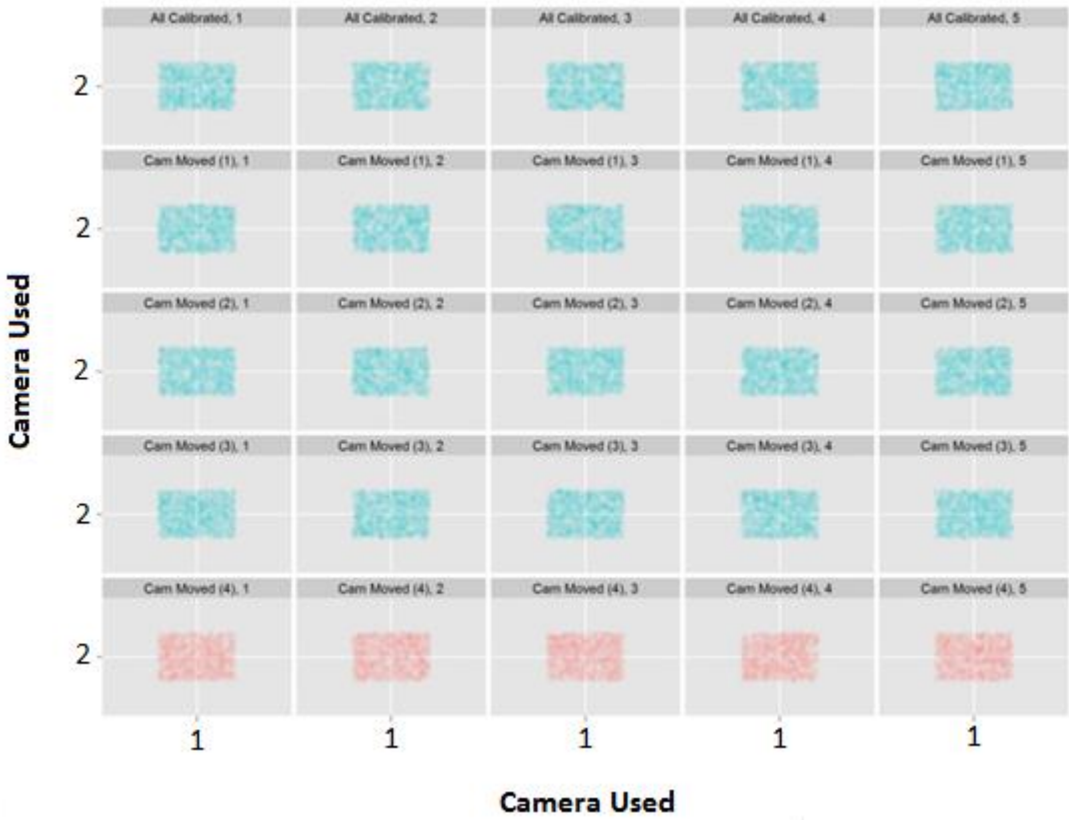

Figure 34: Representation of the tracking of the marker in each sample of all five repetitions: marker tracked (blue) and marker not tracked (red).

The caused distortions on the 3D marker position for each movement in the three dimensions x, y, and z (in millimeters) are represented in **figures 35**, **36**, and **37**. For each case the graph shows the ranges of values for the location given by each repetition and the mean values. It can be seen an increased distortion of the 3D position in the same direction for each movement, and it can be noticed the low variability between all five repetitions.

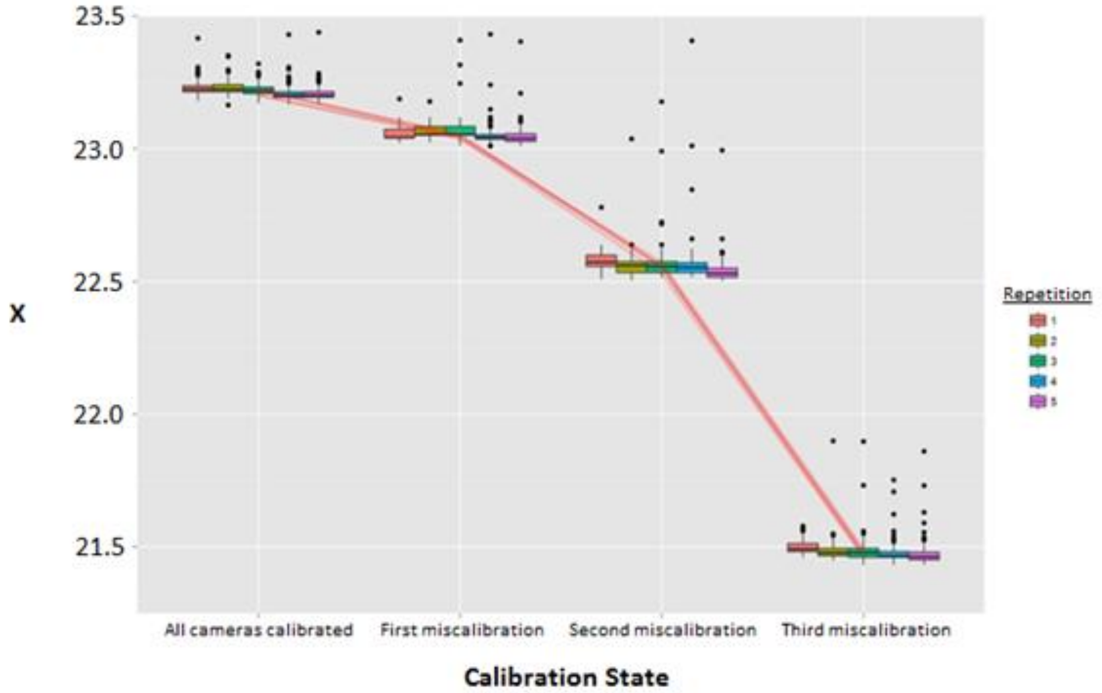

Figure 35: Variation in millimeters of the x coordinate of the 3D position of the marker when moving the camera for each of the five repetitions.

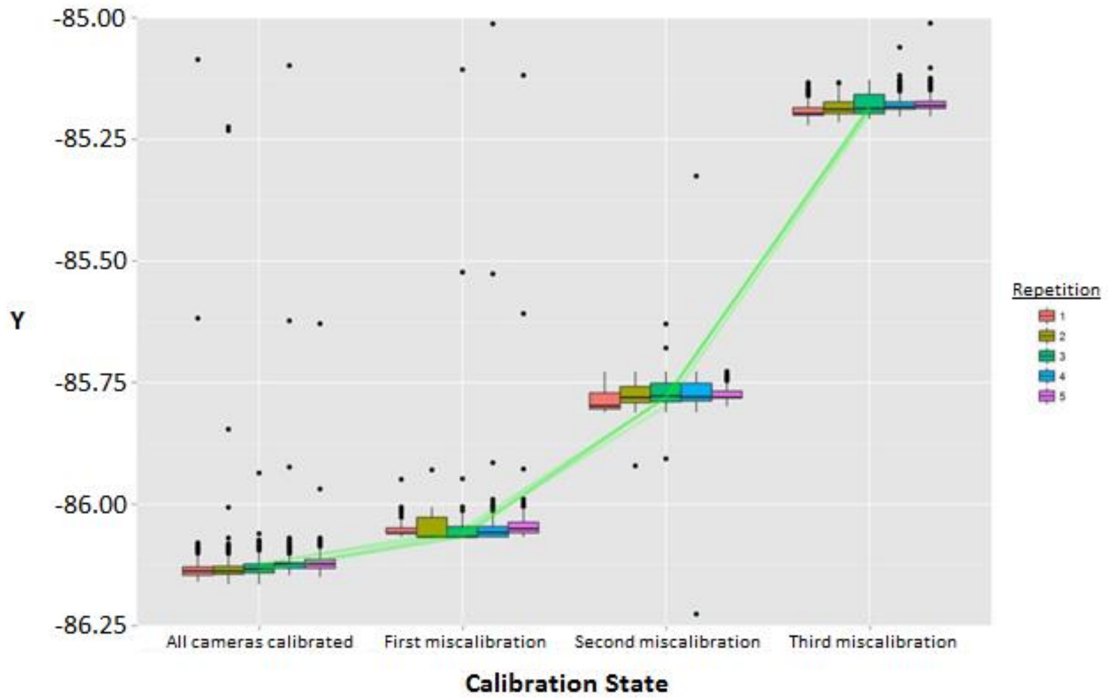

Figure 36: Variation in millimeters of the y coordinate of the 3D position of the marker when moving the camera for each of the five repetitions.

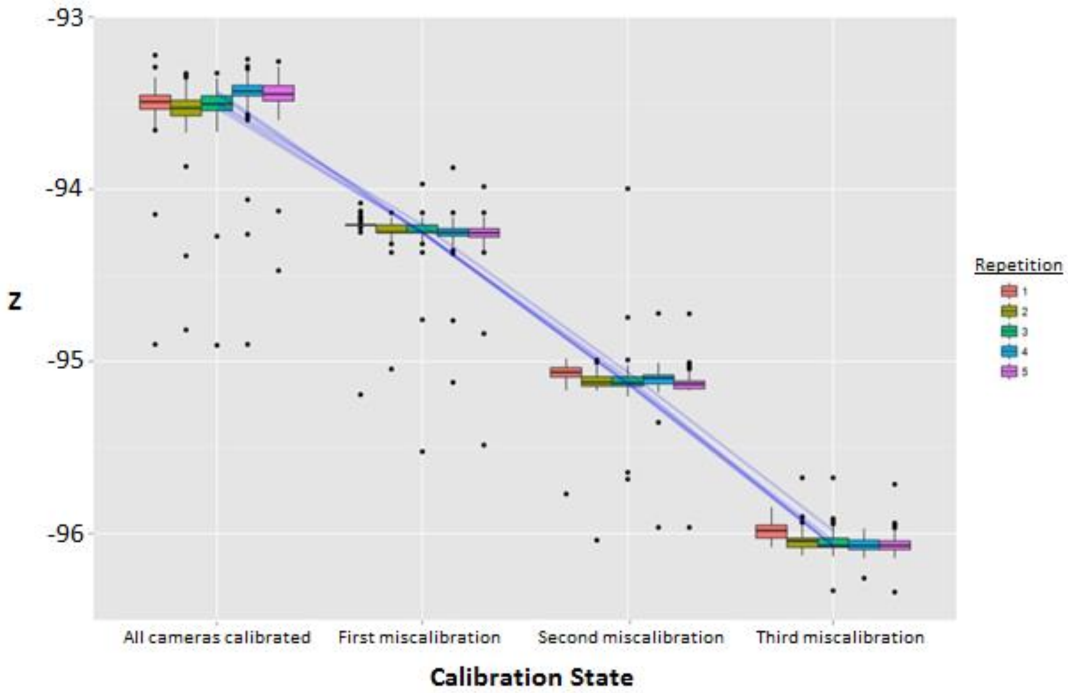

Figure 37: Variation in millimeters of the z coordinate of the 3D position of the marker when moving the camera for each of the five repetitions.

One limitation has been identified in this methodology:

- The OptiTrack cameras used in this experiment (OptiTrack Flex 3) are not exactly similar to the ones used in previous experiment (OptiTrack Flex 13). Their main difference is in the resolution: Flex 13 model has a higher resolution than Flex 3 model. However, this different resolution is not expected to produce serious variations on the results due to the different sizes of the working spaces in both experiments. In camera pairs tracking experiment cameras has greater resolution but they are further from the marker, while in this experiment low resolution is compensated with a marker much closer to the cameras.

Finally, according to the results of the experiment it can be stated the high sensitivity of a two-camera tracking system to miscalibrations. It has been demonstrated that the methodology of the camera pairs tracking approach is able to directly detect miscalibrations in the order of 0.16°. Although not all possible camera movement direction have been assessed, the results of this experiment serve to provide an estimation of the sensitivity of that methodology.

5.2. CALIBRATION TEMPORAL STABILITY ASSESSMENT

The purpose of this experiment is the assessment of the temporal stability of operating room tracking system calibrations. This evaluation will enable to determine if it is possible to define calibration protocols based on calibrating every certain period of time instead of calibrating every day the tracking system is used. The hypothesis was that, if no people access the OR during the time of the experiment, the calibration quality must be maintained throughout the experiment assuming that the scenario to be tracked is stable (no alteration of the tracked scenario).

The variation of the marker 3D position was studied, taking as a gold standard for the experiment the 3D position provided by the tracking system using all 8 cameras just after calibration. This gold standard was compared with all measurements done over time. **Figure 38** shows the variation of the marker position tracked using all available cameras (eight) as a function of time using as a reference the mentioned gold standard. It can be observed how there was a temporal variation on the position. However, there was not an increasing trend, which would indicate a loss of calibration quality with time. This random variation of 3D position along time may be due to vibrations and instability of the system.

The variation of the 3D tracking is below 0.65 millimetres throughout the experiment. This error in the tracking is acceptable according the assessment performed in 2013 with the same optical tracking system [6]. Therefore, it can be stated that the 3D tracking of one reflective marker using all 8 cameras in the operating room along five days is stable. However, as the number of markers increases the tracking error decreases, thus this temporal assessment should be done using rigid bodies composed of a higher number of markers.

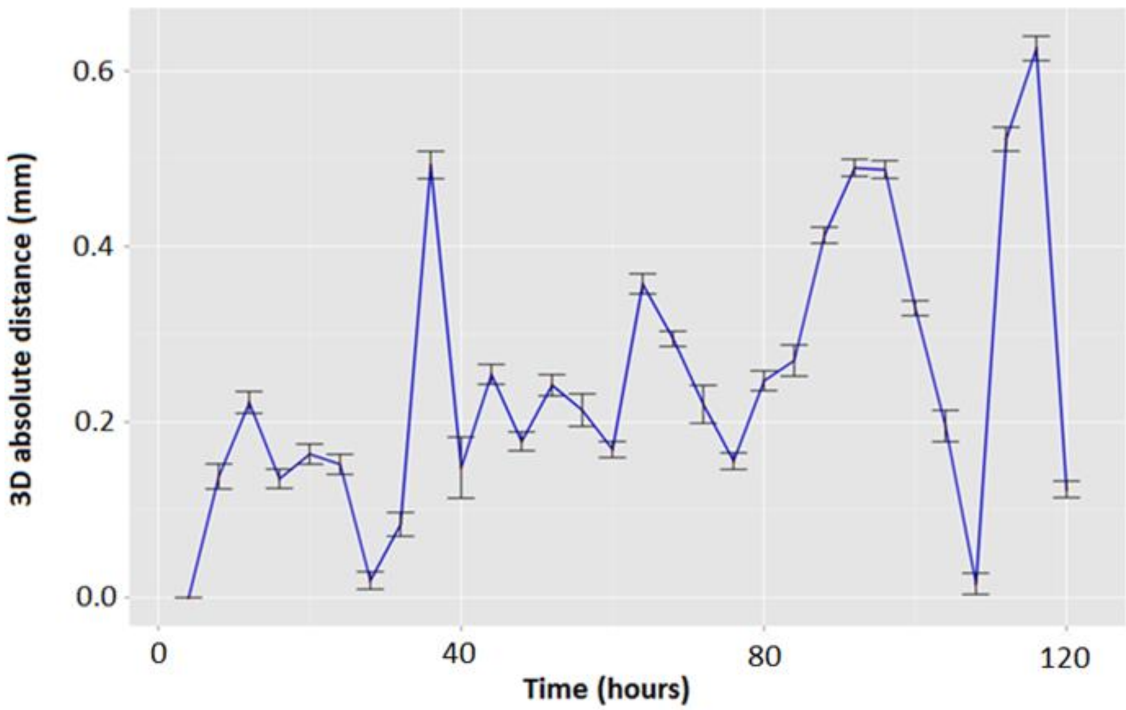

Figure 38: Difference of the 3D position of the marker with time taking as reference the 3D position acquired using all 8 cameras just after calibration.

When assessing the distance to the gold standard from the marker 3D position obtained using every pair of cameras along time, the following results were obtained (**Figure 39**). The radial coordinate represents the 3D distance to the reference, and the angle represents the time, being the different coloured regions the different days of the experiment. The black curve corresponds with the distance using all available cameras, as in **Figure 38**.

It can be seen how the error (distance to the gold standard) using all cameras is the lowest, which was the expected behaviour since in this case the maximum information (eight cameras) was used to compute the 3D position. This error was maintained within the 0.65 mm limit. On the other hand, the errors when using just two cameras remained approximately below 2 mm. Also, it is noticeable that the great majority of camera pairs tracking errors were concentrated in error values closer to the error of the tracking using 8 cameras, while some pairs present much higher error values.

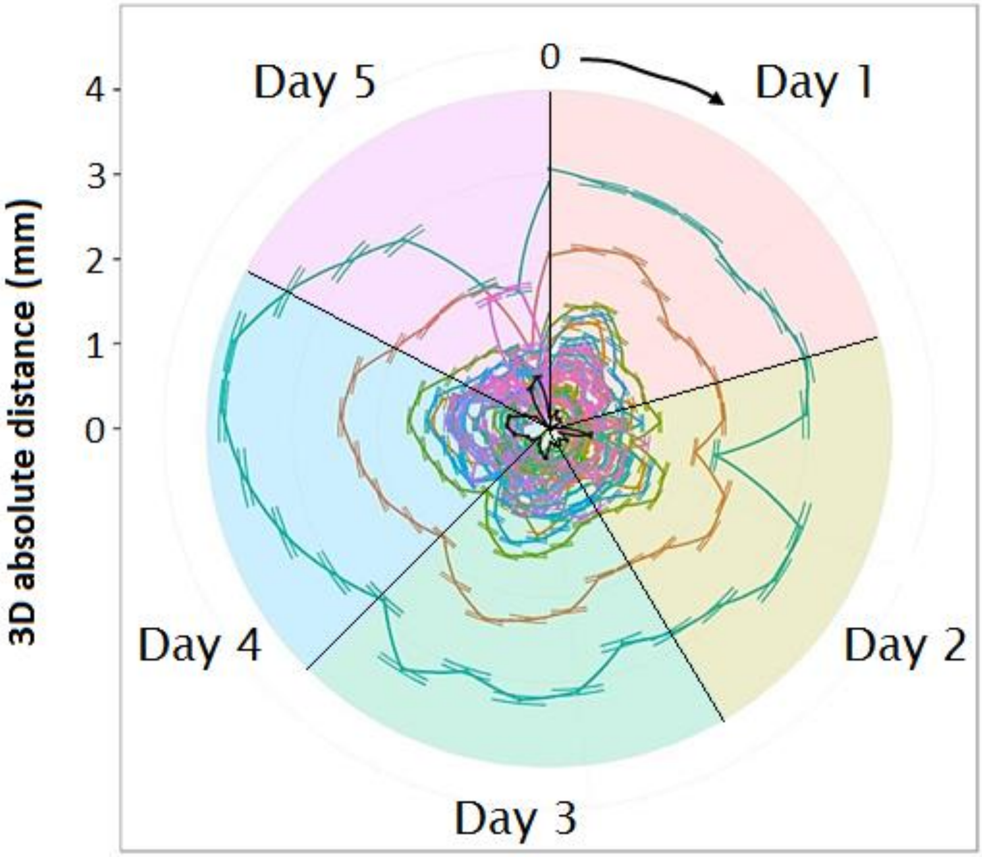

Figure 39: Difference of the 3D position of the marker in time, taking as reference the 3D position acquired using all 8 cameras just after calibration.

By analysing which cameras belong to those pairs producing increased levels of error in **figure 39**, camera 3 is determined to be the cause of this problem. **Figure 40** shows in blue the camera pairs containing camera 3, and in red otherwise.

Camera 3 was found to be miscalibrated after experiment. This camera generated problems during the calibration several times, and after the experiment it was discovered that the camera was not properly fixed. An explanation to the results regarding this camera is that it presented the worst calibration quality, and, due to the unsuitable fixation, the vibrations of the operation room may have miscalibrated it even more. According to the previous experiment (miscalibration quantification experiment), the level of error (~ 3 mm) is small enough for the system to still tracking the marker (**Figure 32**). Also, the results of the previous experiment determined that the angular variation for this level of error to be produced is ~0.10-0.15°, feasible taking into account the bad fixation of the camera.

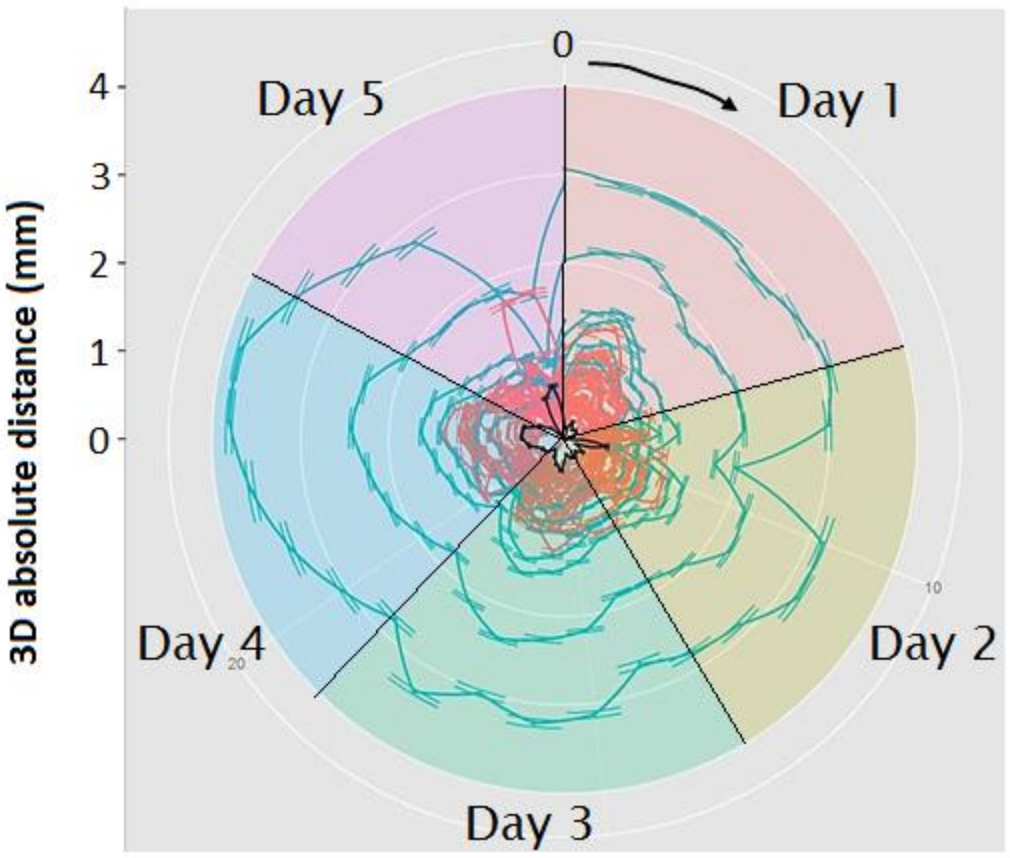

Figure 40: Temporal variation of the 3D position of the marker tracked by all pair combinations of cameras, showing in blue those pairs containing camera 3.

In order to analyse correctly the stability of the calibration along time, errors belonging to camera pairs containing camera number 3 are not taken into account. **Figure 41** shows the behaviour of the error along time for the rest of camera pairs. Error level remained below ~2 mm for all camera pairs, and below 1 mm for the great majority of them. According to these error values obtained along five days, it is demonstrated the feasibility of being able to detect miscalibrated cameras using camera pairs tracking approach 1-5 days after performing the calibration.

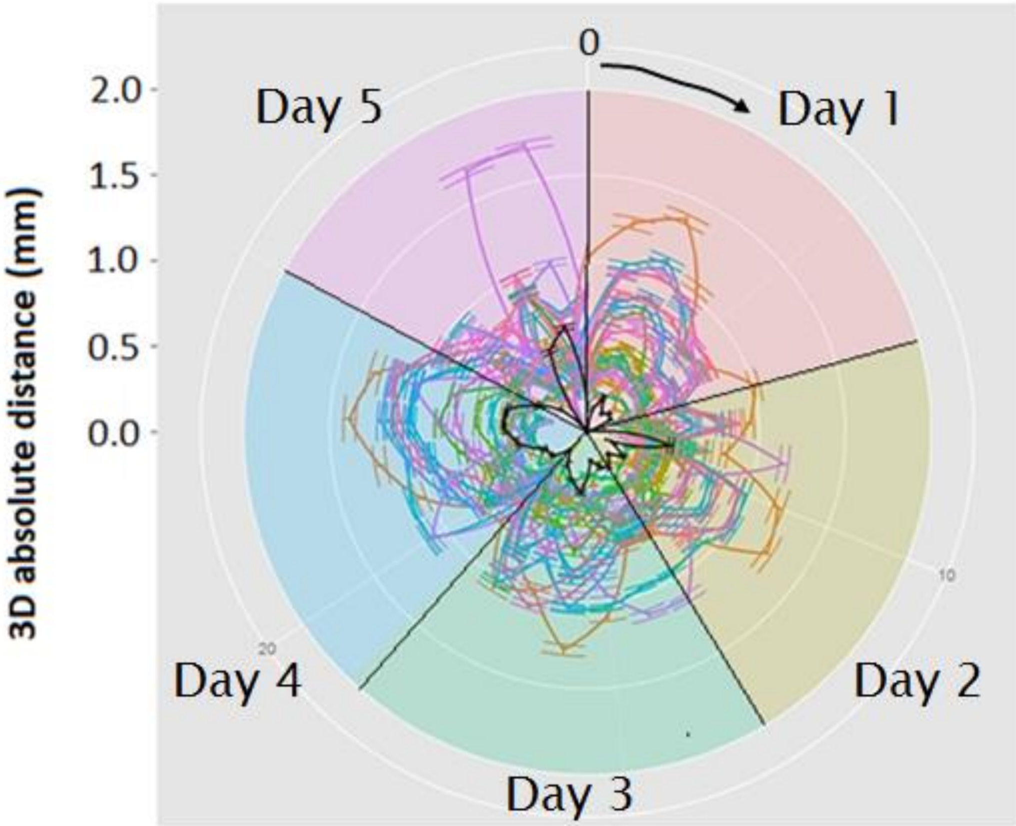

Figure 41: Temporal variation of the 3D position of the marker tracked by all pair combinations of cameras except those pairs containing camera 3.

Finally, the 3D positions of every acquisition along time are shown by representing the projections on the planes: xy (**Figure 42**), yz (**Figure 43**), and xz (**Figure 44**). Black dots represent the positions tracked by using 8 cameras. These results provide a good visualization of the tracking variations. The information regarding the camera pairs containing camera number 3 has not been plotted. 3D positions were maintained within acceptable low error limits.

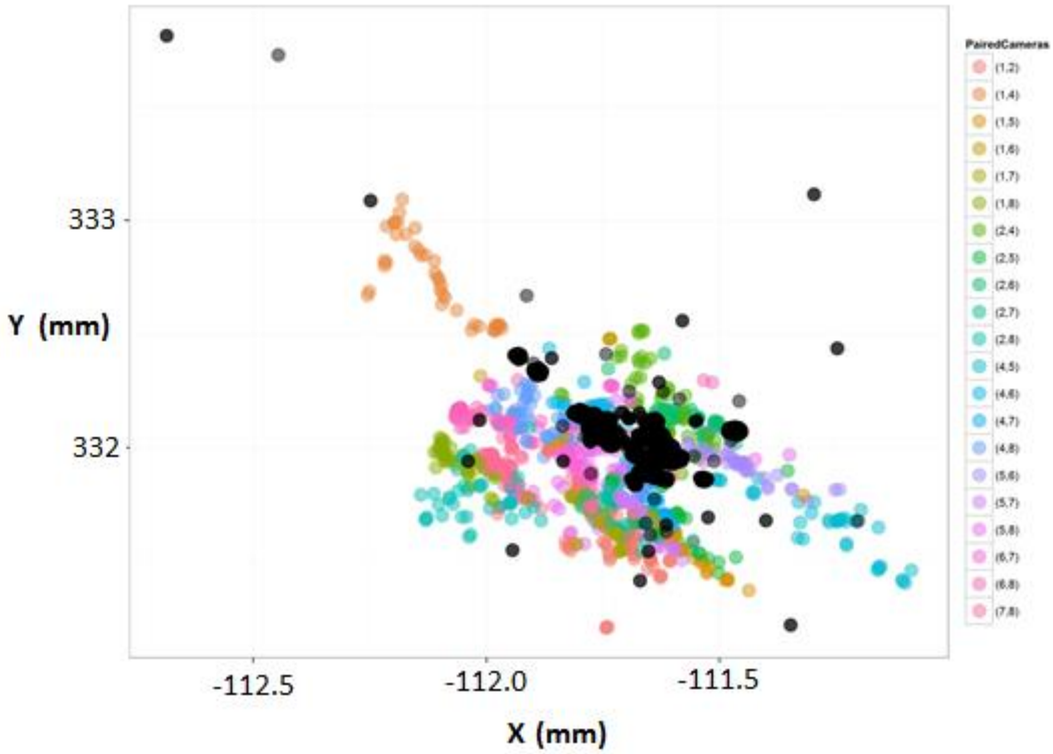

Figure 42: Projections of the 3D positions along time on the xy plane.

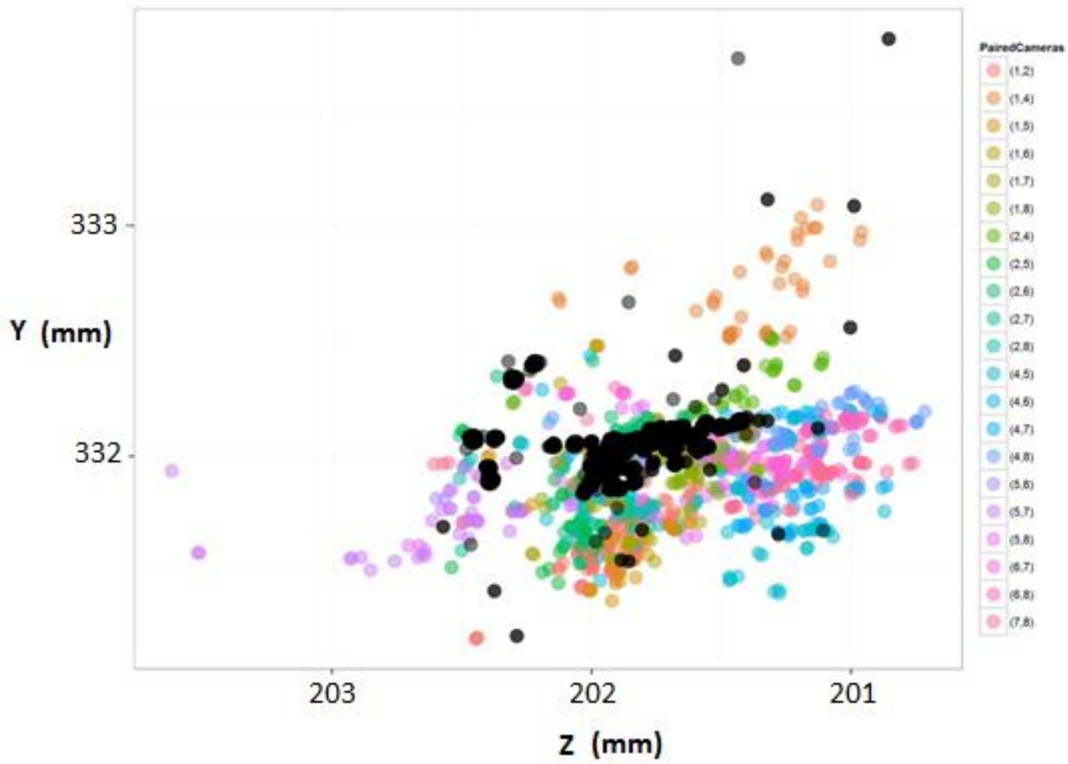

Figure 43: Projections of the 3D positions along time on the yz plane.

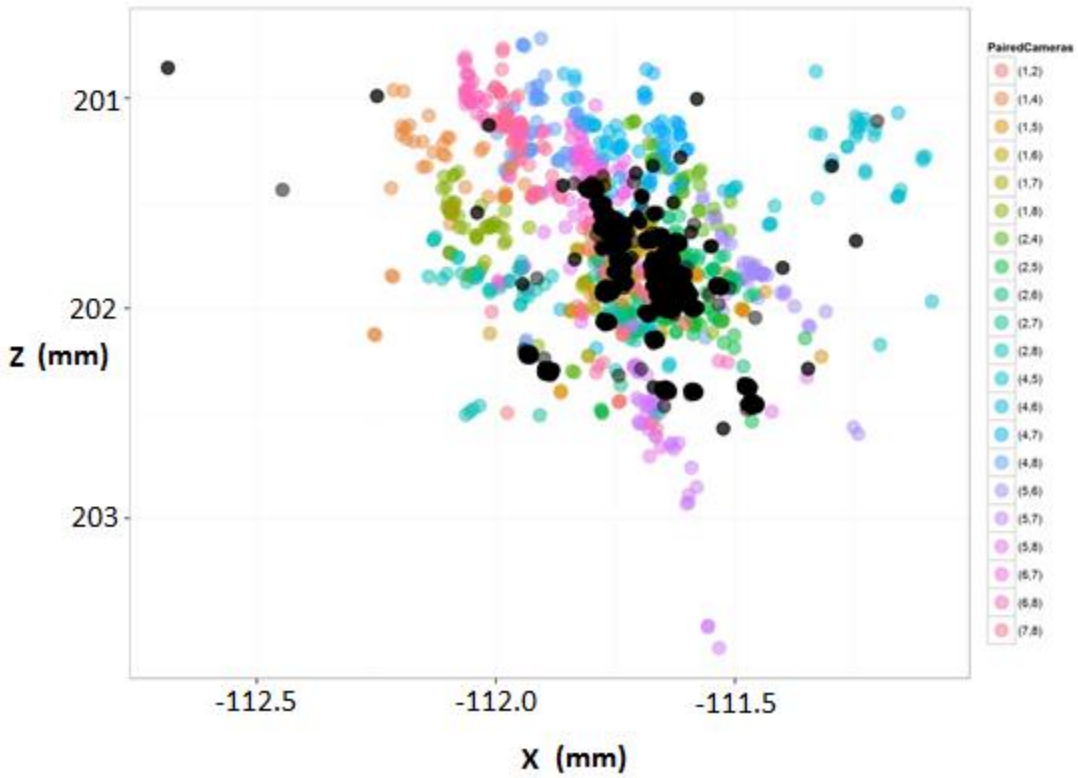

Figure 44: Projections of the 3D positions along time on the xz plane.

According to the obtained results, by studying the difference in 3D position of a static marker along time using the position obtained just after the calibration as gold standard it can be seen that there is variability in the tracking of the marker along time. However, there is not an increase trend in the error with time, but an intrinsic variation around the initial tracked 3D position. Therefore, it can be stated that there is not a tendency of the system to miscalibration.

During the development of the experiment, the influence on the calibration quality of external factors, mainly people entering the operating room, was properly avoided. Then, this discovered intrinsic variation was solely due to unavoidable sources of error: vibrations of the building, temperature, initial calibration error, fixation of cameras, and others. Fixation of cameras was one critical factor affecting the experiment, as it can be observed in the results, since one of the cameras used was not properly fixed generating a higher level of error. As a result, it can be stated that ensuring a proper fixation of the cameras before calibration is a critical and necessary step.

Moreover, the results indicate that the variability of the 3D position acquired by using all eight cameras remained under 0.65 millimetres during all the duration of the experiment (5 days). This variability in the tracking of a single marker was acceptable, but it has to be taken into account that the error will be accentuated when tracking a rigid body of several markers (usually four).

In addition, the level of error when tracking the marker using pairs of cameras was below 2 millimetres in all cases, and below 1 millimetre for the great majority of them. From these results, the proposed camera pairs tracking approach was demonstrated to be feasible along time. Furthermore, the bad fixation of one of the cameras (camera 3) was easily detected by the methodology of this approach, since the tracked positions of the markers with those pairs of cameras containing camera 3 presented a much higher level of error than the rest of camera pairs.

On the whole, once assessed the stability of camera calibration over a 5 days period of time, it can be stated that it will be feasible to perform camera calibration every 1-5 days maintaining an acceptable level of error in the tracking. Moreover, the method for the detection of camera miscalibrations must be performed before any procedure to efficiently detect camera movements (miscalibrations of the system) prior to IOERT treatment in order to minimize as much as possible erroneous tracking arising from external factors. This new methodology proposed for the tracking system preparation before IOERT treatments will reduce preparation time from 60-90 minutes needed before to approximately 5 minutes in those cases where no calibration is needed. Moreover, it will be possible to perform calibration one or more days before the surgery reducing the existing dependence of the operating room availability, which is really low.

5.3. FINAL METHODOLOGY

Taking into account the results of the performed experiments, as well as the limitations of these experiments, a final methodology can be proposed. This methodology will allow users to reduce required time prior to surgery since calibration procedures could be avoided in some cases where the calibration state of the system has been maintained from previous calibration. The following methodology will require approximately 5 minutes to be performed, allowing the users to reduce the tracking system pre-surgical preparation time from 60-90 minutes to just 5 minutes were calibration state has not been altered by external factors.

The diagram below shows the proposed methodology to follow:

Place one optical marker in the center of the working space of the tracking system.

↓

Check that all cameras composing the tracking system are able to visualize the marker. If not, the position of the marker must be changed until it is detected by all cameras of the system.

↓

Obtain 3D marker position using all cameras of the tracking system.

↓

Obtain 3D marker position using all camera pairs combinations of the tracking system.

↓

Detect miscalibrated cameras by studying which pairs of cameras provide a non-valid 3D position.

↓

Detect miscalibrated cameras by studying which pairs of cameras provide a distortion in 3D position (in comparison with the 3D position obtained using all cameras) higher than the predefined threshold.

Firstly, the one-marker rigid body is placed in the operating room approximately in the centre of the working space of the tracking system. There is no need to remove surgical instrumentation unless it is able to reflect IR light disturbing tracking system performance.

Then, using the Tracking Tools software the position of the marker must be checked in order for all cameras of the tracking system to be able to visualize and track the marker. In other words, it is checked whether there is any line-of-sight occlusions or not. In case the marker is not correctly tracked by all cameras, it must be moved in order to fulfil the condition.

The next step is to acquire the 3D position of the static marker using all available cameras in the system. This position will be used as a reference.

Later, the Alternative Tracking Application is run in order to acquire the 3D position using all different camera pair combinations.

Finally, the miscalibrated cameras are detected by:

- Determining which cameras are miscalibrated by checking which pairs of cameras provide a non-valid 3D position, meaning that tracking ability has been lost due to miscalibration of one or both cameras belonging to the given pair.

- Determining which cameras are miscalibrated by checking which pairs of cameras provide a difference in 3D position, in comparison with the reference (using all cameras), higher than the predefined threshold.

6. CONCLUSION

The main objectives of this project were: (1) determining an optimal method (easy and fast) to detect the need for calibration of the tracking system avoiding long delays; and (2) evaluating the stability of tracking system calibration.

The objectives of the project have been fulfilled since the optimal method to detect the need for calibration of the tracking system has been determined, and the stability of the system calibration has been successfully assessed during a 5 days period.

6.1. MISCALIBRATION DETECTION

The two approaches assessed in order to determine the optimum methodology for detecting miscalibrations of the optical tracking system were:

(1) Camera projection error approach: using the camera projection error.

(2) Camera pairs tracking approach: tracking a reflective marker with all different combinations of camera pairs.

According to the results of the experiment to determine the optimal method to detect miscalibrations within the tracking system, it can be concluded:

- The camera projection error approach is not an optimal methodology for detecting miscalibrations since it requires a large number of repetitions to provide reliable results. Then, this methodology does not fulfill the specification of the desired fast method. Moreover, this methodology does not identify miscalibrated cameras.

- The camera pairs tracking approach consisting on alternative tracking of a single static marker with all different pair combinations of cameras within the tracking system is demonstrated to be feasible for detecting miscalibrated cameras. Moreover, this method is fast, reproducible, and no prior knowledge is required. Therefore, it is selected as the preferred methodology to follow.

- The high sensitivity of camera pairs tracking approach has been demonstrated, it is able to directly detect miscalibrations in the order of ~0.16 millimeters for the given scenario.

- The camera pairs tracking approach methodology is able to instantly detect and identify large miscalibrations within the system, while smaller miscalibrations require the predefinition of a threshold value for the maximum tolerance of the system to 3D tracking error.

6.2. CALIBRATION TEMPORAL STABILITY ASSESSMENT

According to obtained results regarding the evaluation of the temporal stability of the calibration of the tracking system in the operating room, it can be concluded that:

- There is no tendency of the tracking system to miscalibration, but an intrinsic variation of the tracking position as a result of unavoidable sources of error such as vibrations of the building, temperature changes, initial calibration error, fixation of cameras, and others.
- The variability of the 3D position acquired by using all eight cameras remained under 0.65 millimetres throughout the experiment (5 days). This variability in the tracking of a single marker was really low, and it is within acceptable limits of error.
- The camera pairs tracking approach methodology has been demonstrated to be feasible along time since the tracking error is below 2 millimetres for all cameras, and below 1 millimetre for the great majority of them. Moreover, this methodology was able to easily detect a miscalibrated camera, during the temporal stability assessment, days after the calibration.
- The demonstrated temporal stability of the tracking system calibrations enables to perform camera calibration every four or five days maintaining an acceptable level of error in the tracking.

To conclude, once the stability of camera calibration has been assessed over a 5 days period of time, it can be stated that it will be feasible to perform camera calibration every four or five days maintaining an acceptable level of error in the tracking. Moreover, the method for the detection of camera deviations must be performed before any surgical/clinical procedure to efficiently detect miscalibrations prior to treatment in order to minimize as much as possible erroneous tracking arising from external factors. This new methodology proposed for the tracking system preparation before IOERT treatments will reduce preparation time from the 60-90 minutes needed before to approximately 5 minutes in those days where no calibration is needed.

Therefore, the results obtained from the experiment performed during this project will allow the hospital to define new protocols for calibration performance based on calibrating every certain period of time (1-5 days). These new protocols will enable the hospital to save time and resources.

7. PROJECT BUDGET

The estimated costs of this project come from the equipment used and from the human resources (Bachelor coordinator and student).

❖ Equipment Costs

The following table shows the material used in the project with a depreciation of 20% at five years.

EQUIPMENT	UNITS	COST (€)	COST/YEAR (€)	DEDICATION	TOTAL COST (€)
Camera Flex 13	8	7166.40	1433.28	6 months	716.64
Camera Flex 3	2	1074.24	214.85	6 months	107.42
OptiHub 2	3	816.33	163.27	6 months	81.63
USB Cable	10	89.70	17.94	6 months	8.97
Manfrotto	10	753.20	150.64	6 months	75.32
Stolmen Post	2	53.80	10.76	6 months	5.38
OptiWand kit	1	268.11	53.62	6 months	26.81
Software	1	895.80	179.16	6 months	89.58
Hardware Key	1	88.77	17.75	6 months	8.88
Phidget Sensor	1	125.54	25.11	48 hours	0.14
TOTAL					**1120.77**

❖ Human Resources Costs

The cost associated with the personnel:

PARTICIPANTS	SALARY (€/HOUR)	HOURS	TOTAL COST (€)
Project coordinator	35.00	470	16450.00
Bachelor student	25.00	535	13375.00
TOTAL			**29825.00**

- **Total Costs**

PROJECT PART	COST (€)
Equipment	1120.77
Human Resources	29825.00
PROJECT TOTAL	**30945.77**

8. FUTURE WORK

A single marker has been used for the assessment of the stability of the calibration. As commented, a smaller error will arise from the use of a higher number of markers. In the real IOERT scenarios, a rigid body of four markers is usually used for the tracking of the applicator. Therefore, an experiment in order to assess the temporal stability of the calibration by using a rigid body containing four markers will be useful.

Moreover, an evaluation of the proposed method performance when varying the location of the static marker to different positions in the FOV would be necessary for a more precise definition of the methodology to follow for calibration failure detection.

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10. GLOSSARY

3D: 3 dimensions

2D: 2 dimensions

API: Application Programming Interface

BiiG: Biomedical Imaging and Instrumentation Group

CT: Computed Tomography

DLL: Dynamic Link Library

EBRT: External Beam Radiation Therapy

EMTS: Electromagnetic Tracking System

FOV: Field Of View

HGGM: Hospital General Gregorio Marañón

IGS: Image-Guided Surgery

IOERT: Intra-Operative Electron Radiation Therapy

IQR: Interquartile Range

IR: Infrared

MR: Magnetic Resonance

LED: Light-Emitting Diode

LIM: Laboratorio de Imagen Médica

LINAC: Linear Accelerator

OR: Operating Room

OTS: Optical Tracking System

SD: Standard Deviation