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DESIGN OF A MEASUREMENT SYSTEM FOR THE ESTIMATION OF THE KNEE KINEMATICS

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ABSTRACT

Through the use of Axiomatic Design, a measurement system to evaluate the kinematics of human joints was developed. In this paper the needs of Université Libre de Bruxelles (ULB) are analyzed in order to build a measurement system able to evaluate the position of infrared marker in space. A system of 10 cameras, produced by Optitrack, able to track infrared reflective bodies, has been configured and optimized to measure the movement that happens within a known volume, calibrated, where it is possible to position joints using appropriate fixtures, so that it is possible to evaluate the kinematics without constraints that could modify the natural movements.

Keywords: Biomechanics, Axiomatic Design, Kinematics.

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1. INTRODUCTION

In the current trend, where life expectation is increasing, the incidence of bone and joint diseases it is no longer negligible as they cause difficulties or in the worst case the complete block in movement.

As consequences several companies have started to invest in prosthesis that are as much as possible able to replicate the physiologic condition of the joint in order to improve comfort in the everyday activities, less stress for the body to adapt to new movement and, as consequence, longer durability of the implant itself. With the development of 3D modeling and scanning, associated to manufacturing technologies as the 3D printing [1], we are living the revolution where the prosthesis might even be custom made for the person that needs it.

Today indeed it is possible:

1. Evaluate joint's 3D geometry in real time in living people using scan technique as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI);
2. Evaluate the movements of joints and the way articular surfaces interact during the move;
3. Produce fast and without being obliged in huge adaptation in the machine, maintaining the same reliability of traditional technique as milling and turning, with the advantage of having something custom made.

In this contest the problem of measuring movements is largely studied in Laboratory of Biomechanics of those companies where the prosthesis is built, as it will make the difference in the process of creating custom made devices that will assure the maximum of the durability causing the minimum stress in the host.

As already developed by the authors in other works [2], the literature provides many holistic approaches that can study engineering problems. Therefore, a statistical approach, such as in [3], could help to know in depth the relationship among parameters.

Across this paper the steps necessary to develop an optical measurement system, able to evaluate the position of special infrared markers, are explained with the perspective of the Axiomatic Design, used to make the match between the initial request with the final product. The aim of this paper is design a system that is able to capture the position of some markers detectable by infrared camera, so that it will be possible to evaluate the kinematics of joint placed in an identified and appropriately calibrated volume.

2. MATERIALS E METHODS

The approach used to develop the system is the Axiomatic Design (AD) [4-7]. Following AD it is possible to evaluate all steps in a rigorous way avoiding forgetfulness or errors of evaluation in the choices made. The study is based on the principles of the Axiomatic Design [8, 9], which is investigated here through its practical relevance in Biomechanical applications.

At the basis of AD there is the division of the process of development in 4 domains (Figure 1).

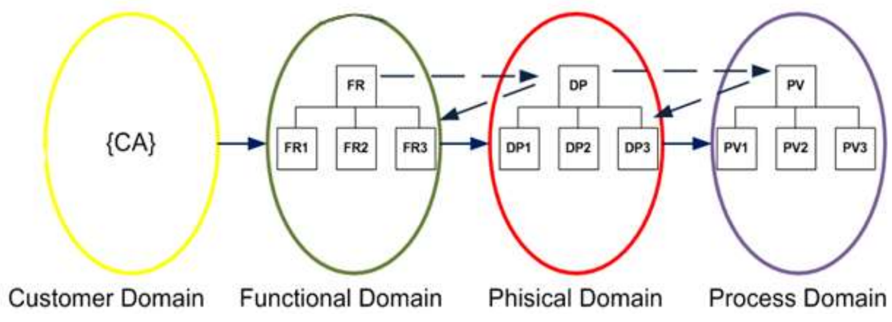

Figure 1 The 4 domains of AD [10].

The design world is made up of four domains: Customer Domain, Functional Domain, Physical Domain and Process Domain. These represent the domain where the concepts "WHAT we want to achieve" and "HOW we want to achieve it" lie (Figure 1). To define the WHAT concept, one starts from the Customer Domain, characterized by Customer Attributes (CAs) the customer is seeking in a product or system, and transforms them into a minimum set of independent requirements that completely characterize the functional needs of the product: Functional Requirements (FRs). Actually, in Functional Domain, CAs are specified in terms of FRs and Constraints (Cs), defined as bounds on acceptable solutions (imposed as part of the design specifications or by the system in which the design solution will function). In order to satisfy the specified FRs, Design Parameters (DPs) were chosen for the Physical Domain. Finally, to produce the product specified in terms of DPs, a process, characterized by Process Variables (PVs) in the Process Domain was developed.

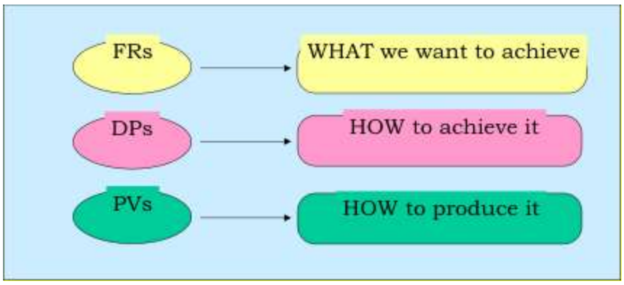

Figure 2 Meaning of the different variables related to the domains [11]

The strength of AD is the fact that the data flow does not follow a direction in a way that errors in the design project are developed in the first prototype. In AD all parameters are evaluated in each step in a way that correlation is highlighted in a way that if a parameter is related to another the process will require a rework so that all parameter will be independent. A strong mathematic formulation will help avoid mistake by giving to the developer a high level of detail. To do so each domain can be divided in subdomain connected by arrows that will move from a domain to another until the project is completely open and clear.

3. SYSTEM DEVELOPMENT

3.1. Identification of the Customer Needs

In the specific application the Customer Needs or Customer Attributes identified for the system are:

1. Being able to use many cameras at the same time in order to have the possibility of analyse in the most precise way as possible different kind of movement of rigid body in the volume of interest;
2. The position of the camera has to be fixed, so that between measurements there is no need of recalibrate the system, but has to be flexible (the user can choose the volume);
3. The position of the cameras should allow the presence of two operators during tests;
4. It has to be foreseen a system that can allow to block bones;
5. The whole system should be used along with other system used in the lab.

Then the second step is the identification of Functional Requirements: the translation from the CAs to the FRs has to keep alive the Axiom of independence. For this reason, the FRs have to be independent in a way that no FR depends on other FRs. The specifications of the test bench are summarized in a column vector that will represent the FRs for this project, as follows:

$$\{\boldsymbol{FRs}\} = \begin{Bmatrix} \boldsymbol{many\ pivoting\ cameras} \\ \boldsymbol{Double\ access\ side} \\ \boldsymbol{Multidevice} \end{Bmatrix} \quad (1)$$

The three FRs are considered the minimum number that satisfies the CA.

3.2. Identification of the Constraints

The cameras available at the Laboratory of Biomechanics at the ULB are Optitrack Flex3. In particular there are a maximum of 10 cameras available.

The parameters highlighted in green show the limits in the image acquisition as for sampling rate (Frame Rate: 25, 50, 100 FPS) and precision. The constraints due to the camera are important as they limit the max speed that can be recorded (Frame Rate: 25, 50, 100 FPS) during the test and set an important parameter in terms of distance, as the bigger is the distance, smaller will be the precision recorded, as it is expected a precision of the sub millimeter. On the other hand, physical constraints of the lens (Field of View: Horizontal=38.0°, Vertical=28.5°) implies that the object should not be too close as this would make difficult the following of the object with two cameras in a volume as big as the one that it is intended to be measured.

One more constraint is the fact that to have a significant record of movement, which should be in 3 dimensions, at least two cameras should be able to record the movement of the markers. Moreover, the biggest is the number of cameras that are able to spot a marker better is the precision achieved.

Last consideration is that users of the device in sight of the camera should not wear anything that could reflect infrared light. Lights, and the camera themselves should not be in the sight of other cameras.

The vector of constraints is then

$$\{\boldsymbol{Constraints}\} = \begin{Bmatrix} \boldsymbol{Distance} \\ \boldsymbol{Pointing} \\ \boldsymbol{Interference} \end{Bmatrix} \quad (2)$$

3.3. From FRs to DPs

In the transformation from FRs to DPs it is necessary to choose the working volume of the system so that the distance among the cameras could be adequate. That is necessary because of the constraints fixed in the paragraph above. The working volume of the system has been fixed as a cube of 0,5m per side.

A few tests, performed on temporary fixture shown that fix 8 cameras fixed in the corner of two squares with one side in common, with the length of 1m per side, plus two cameras fixed in the center of the square, would be able to record the requested volume.

The equation that we want to have to verify the system is shown below:

$$\{\boldsymbol{FRs}\} = [\boldsymbol{A}]\{\boldsymbol{DPs}\} \quad (3)$$

It is necessary then to build the DPs and the matrix that, for the structure given to this project, will be diagonal.

The process that is followed implies that the process is iterative where we move from one to another domain breaking the FRs requirements if necessary in order to simplify the work and have more detail of what needs to be done.

FR1: Each camera should has his own pivoting system.

DP1: Each camera should be allowed to rotate with two degrees of freedom

FR2: The Test bench should have 2 sides free.

DP2: The length and the positioning of the structure should allow the presence of more people around the device.

FR3: Possibility of being used with other devices.

DP3: It is needed to have a place where another object can lie.

FR31: Need to host one or more computer and other devices necessary for data acquisition.

DP31: The bench should have one or more areas where tools can be stored. Three areas are identified. The first will host acquisition devices, the second will host the tools needed and the third it is the area where the test is performed.

FR32: Need to have an interface that would allow other devices to be used for tests.

DP32: The bench should have an area that could hold a knee simulator, that should be washable and that should allow the best positioning, that should be then fixed, to allow the best visibility.

The choice of the FRs allow the matrix A to have a diagonal form like the one below:

$$[A] = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \quad (4)$$

As consequence to each FR corresponds a DP. The correspondence is two ways. This applies also to the sub parameters developed.

The diagram in Figure 3 shows what explained in words.

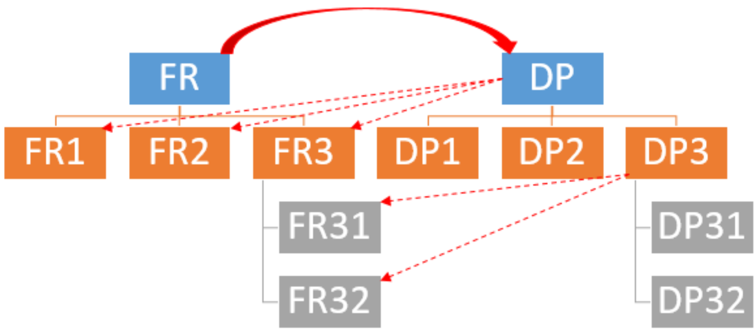

Figure 3 Relazioni tra i Requisiti Funzionali ed i Parametri di Progetto sviluppate per questo studio

By using the mathematical structure that characterize the Axiomatic design we will have the following result:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \quad (5)$$

That applies also for the sub functional requirements and design parameters:

$$\begin{Bmatrix} FR31 \\ FR32 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \end{Bmatrix} \quad (6)$$

As the number of parameters appears to be the minimum, (all requirements are satisfied, and no parameter is repeated) also the Axiom of information is satisfied.

3.4. Evaluation of PVs

In the Process Variables are defined all the technological parameters that will be developed to realize the project before being delivered to the client. It is important then define and justify the choices that have been taken in the previous steps in order to be sure that all requirements are satisfied, once more.

As done in the previous part all parameters will be pointed and developed with a proper counterpart in the Process Variables domain.

DP1: Each camera should be allowed to rotate with two degreed of freedom

PV1: To hold the camera in position and create the two squares with a side in common, independent from the rest of the system, standard aluminum profile 20mmx20mm like the ones shown in Figure 4 where chosen.

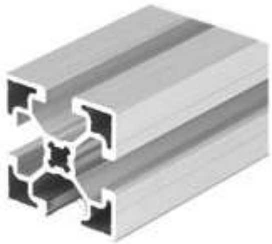

Figure 4 Aluminum profile used to create the bench and the holding system for the cameras

A total of 9 profile where used. 6 of them 0.96m long, 3 of them 1m long. This choice will satisfy the principle of having, whatever camera is choice, at least 1 camera that is 1m far away. The choice of the profile comes from the flexibility that this profile offers in term of fixing more devices if needed using T screws. To have the correct number of degree of freedom L profile, easy to find in every bricolage store, keeping the prices as low as possible. The thickness of the profile is 2mm, the material is aluminum. Any deformation due to the weight of the camera, as the system is not moving or vibrating, will not be considered as the calibration is done after the camera are fixed in position.

Connection between camera and profile is done with the standard M6 screw given with the camera itself (Figure 5). In this way it is possible to have the 2 degrees of freedom required.

DP2: The length and the positioning should allow the presence of more people around the device.

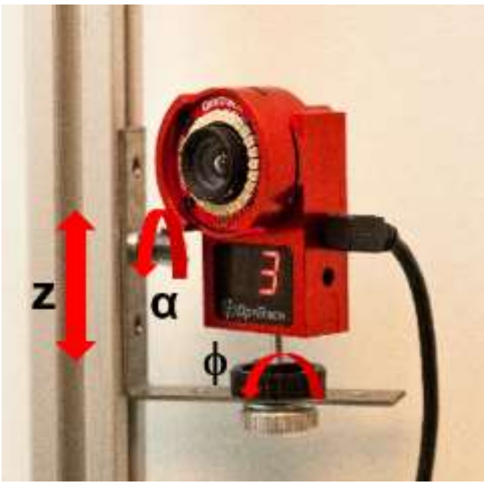

Figure 5 Fix system of the camera that allow the rotation in two directions

With the constrain of having a minimum distance of 1m, it was decided that having an L shape would be the best solution in order to have space for two people to manipulate items and have a complete view of the area of interest

The created system has furthermore the possibility of being moved, as it was forecasted the possibility of move this system from one Laboratory to another. As there was no table able to host the system in a safe way it has been first assembled and placed temporary and tested on the ground.

DP3: It is needed to have a place where another object can lie

DP31: The bench should have one or more areas where tools can be stored. Three areas are identified. The first will host acquisition devices, the second will host the tools needed and the third it is the area where the test is performed.

DP32: The bench should have an area that could hold a knee simulator, that should be washable and that should a low the best positioning, that should be then fixed, to allow the best visibility.

In order to make the measuring system comfortable from an ergonomic point of view it is necessary that it can be used in an easy way from sitting or standing. Consequently, it was necessary to create a structure that had the following characteristics, additional to that specified explicitly, but implied as necessary for a correct functioning of a measurement system.

1. The table should be big enough to host the L that support the cameras.
2. Stable enough with the target of avoid error due to vibration.

Once more it was decided to use aluminum profile, with the dimension of 45mm x 45mm. The profile is the same as the one used previously, with the addiction of rubber feet. With the target of have a system that is independent the table has been designed in a way that two different area are identified. The first one that host the measurement system with the cameras the second one has is equipped with a chipboard 2cm thick, where the equipment can be placed.

The overall dimension of the table is 1,8m of which 0,7m are dedicated to the chipboard. The rest of the table is partially occupied with other aluminum profiles that are able to sustain heavy structure.

By using the same assumption made before the [DP vs PV] matrix will also be an identical matrix.

The mathematical formulation is noted below:

$$\begin{Bmatrix} \boldsymbol{DP1} \\ \boldsymbol{DP2} \\ \boldsymbol{DP3} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{X} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{X} \end{bmatrix} \begin{Bmatrix} \boldsymbol{PV1} \\ \boldsymbol{PV2} \\ \boldsymbol{PV3} \end{Bmatrix} \tag{7}$$

$$\begin{Bmatrix} \boldsymbol{DP31} \\ \boldsymbol{DP32} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{X} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{X} \end{bmatrix} \begin{Bmatrix} \boldsymbol{PV31} \\ \boldsymbol{PV32} \end{Bmatrix} \tag{8}$$

The result of the work is shown in Figure 6.

Figure 6 Overview of the system after assembly

3.5. Validation of the measurement system.

For each point of the calibration tower 3 acquisitions were performed. A 3 steps verification was performed, from graphic to analytical. The procedure of testing was defined as follows:

Each point of the calibration tower was checked with the feeler in a way that the 4 markers fixed with the feeler describe a part of a sphere, avoiding as much as possible discontinuity.

As first step it was verified that the acquisition was consistent. The same point acquired 3 times was plotted in a regular xyz graph using MatLab. An example of the results is shown in Figure 8.

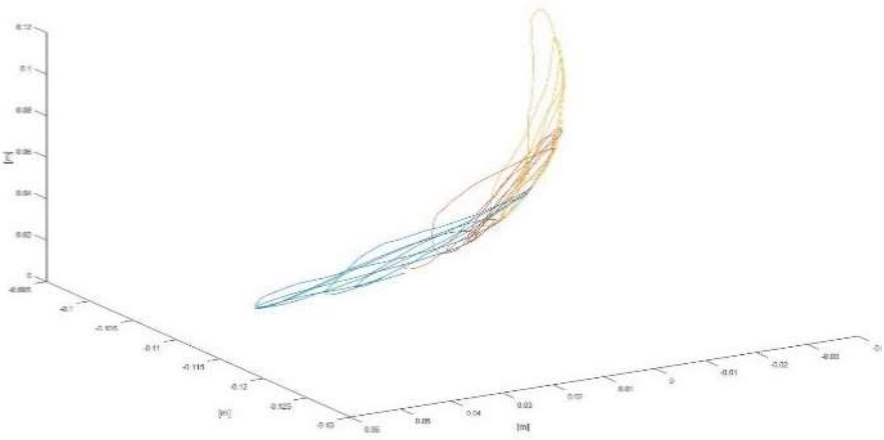

Figure 8 Plot of the coordinate of the same point during data acquisition

Secondly, it was verified that the center point of the sphere are correct. For this reason, another MatLab script was developed in order to identify the center of the sphere that all the markers describe. Consistency in measurement is expected in this phase. All center points should describe the center of the spots designed in the calibration tower. The result of this test is shown in Figure 9.

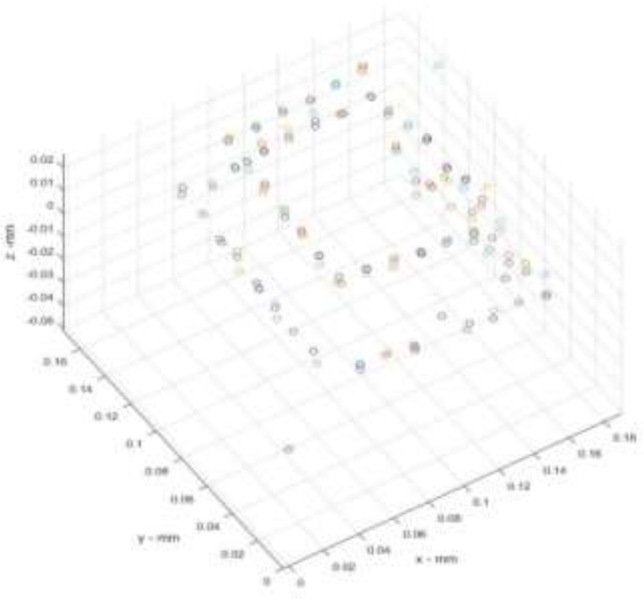

Figure 9 Overview of all acquisition: 1-point is out of range with a detected special cause

In the last analysis were taken some random spot and an average of the coordinate was calculated for different center point. Then the increment was evaluated and compered with the ones known of the device. Figure10 and Table 1 report a summary of this analysis.

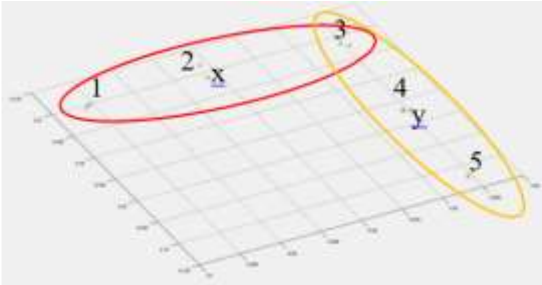

Figure 10 5 points were used to evaluate the precision of the data acquired. Directions are alighted in yellow, where an increase is out of 3-coordinates there should always be 2 that increase. Z is increasing always of 1mm, x or y of 15mm

Table 1 Coordinate of the acquired point when using as origin point 1

	X [mm]	X average errors [mm]	Y [mm]	Y average errors [mm]	Z [mm]	Z average errors [mm]
1	0	0	0	0	0	0
2	-14.5757	0.424294	0.192031	0.192031	-1.29363	-0.29363
3	-30.8048	-0.80481	-0.08814	-0.08814	-2.39836	-0.39836
4	30.568	-0.56796	-15.2395	-0.23951	-3.62426	-0.62426
5	-30.6035	-0.60348	-30.4137	-0.41373	-4.44452	-0.44452

5. CONCLUSIONS

The developed system is coherent with the requirements of the Clients and has shown the required precision and flexibility. Anyway, there are a few improvements that can be performed, especially from a software point of view.

The average error recorded on the 3 axis is 0,3mm, and the max error still remains lower than 1 mm, which is a good precision for the typology of test that will be performed, where the insertion error is due to the difficulties of identify the point of interest because of the soft tissue that envelopes the joint.

Weakness and strength are analysed below. As strength of the system it was remarked:

- Easiness in use;
- No need of calibration each time tests are performed if cameras are not moved;
- Easiness of the calibration process;
- The data are easy to use if the good settings are selected during exportation;
- It is possible to record images and film over data and coordinate so that the process of testing is shown as well as the results.

Below are shown the weaknesses:

- Limited angle recordable by each camera;
- Low resolution compared to modern models of camera of the same supplier;
- No in-house tools for analyse the data.

Improvement that can be developed in order to improve the utilization:

- Acquisition system coordinated in MatLab so that the data and the analysis can be performed in real time;
- Devices that can perform the test without the interaction of a person during the test itself;
- Evaluate the environment in order to improve the way data are recorded and eliminate interferences.

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