Preliminary Study of a Surgical Navigation with Point Based Registration Method
Nokta Tabanlı Eşleştirme Yöntemi ile Bir Cerrahi Navigasyon Ön Çalışması

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Abstract— **By the help of technological advances such as the development of computer and imaging technologies, surgical navigation has started to be used rapidly in medical literature. It is one of the recent methods used to track surgical tools inside the operation volume. In light of vital advantages as operation safety, minimally invasive application compatibility, reduction of operation times and reduced post operation complication risks, surgical navigation has been rapidly adopted throughout the relevant fields. Considering these, this study both tries to apply an introduced analytical method to one of the most important steps of surgical navigation as registration and compares the results within the scope of application compatibility. Throughout the study, a solid model with known dimensions was placed inside a capture volume in which the motion cameras are able to provide position measurements. Carrying out point based registration method by taking necessary measurements, relation between the model reference and measurement space reference was calculated by means of a transformation matrix. Using acquired relationship, measured landmark positions of the model were compared with the structurally known real landmark positions. At the end of the study results were given and the applicability of the introduced analytical solution method in point based registration is discussed.**

Keywords— medical robotics; surgical navigation; point based registration; motion capture.

Özetçe— **Bilgisayar ve görüntüleme teknolojilerinin gelişmesiyle medikal alanda hızla kullanılmaya başlayan cerrahi navigasyon, operasyon hacminin takibinin sağlanmasında kullanılan güncel medikal yöntemlerden biridir. Uygulama esnasında cerrah ve hastaya sağladığı, operasyon güvenliği, minimal invaziv uygulama uyumluluğu, operasyon sürelerinin ve uygulama sonrası komplikasyon risklerinin azaltılması gibi önemli avantajlar ışığında cerrahi navigasyon ile takip, ilgili alanlarda hızlı bir şekilde benimsenmiştir. Bu çalışma, cerrahi navigasyon sürecinin uygulanabilmesi için gereken en önemli adımlardan biri olan eşleştirme prosedürünün analitik çözüm yöntemi ile gerçekleştirilmesi ve elde edilen sonuçların uygulama uyumluluğu kapsamında karşılaştırılmasını içermektedir. Çalışma kapsamında boyutları net olarak bilinen katı bir model, hareket yakalama kameralarının takip edebildiği ilgili uygulama hacmine yerleştirilmiş, ardından nokta tabanlı eşleştirme yöntemi kullanılarak cerrahi navigasyon için gerekli olan gerçek model referansı ile hareket yakalama kameralarının yeraldığı ölçüm uzay referansı arasındaki ilişki bulunmuştur. Dönüşüm dizeyi olarak elde edilen bu ilişki kullanılarak, gerçek model üzerinde yer alan belirleyici bölge noktalarının gerçek konumları ile ölçüm verileri ile elde edilen nokta konumları karşılaştırılmış ve analitik çözüm yönteminin nokta tabanlı eşleştirmede uygulanabilirliliği tartışılmıştır.**

Anahtar Kelimeler—medikal robotik; cerrahi navigasyon; nokta tabanlı eşleştirme; hareket yakalama.

I. INTRODUCTION

The most important fact that affects the success of surgical procedures in medical field can be given as the quality of visual feedback that is acquired form the surgical workspace. Utilization of the tools as surgical lighting equipment and surgical glasses with loupes in classical open surgeries let surgeons focus inside the target areas efficiently due to the fact that it is not an easy task to capture details with bare eyes in regular lighting conditions. On the other hand these classical methods are not efficient in minimally invasive surgeries as the surgeons are operating in closed environments as in the laparoscopic surgeries. In these conditions visual feedbacks are mostly provided through the endoscopic cameras that also reserve their disadvantages as depth loss in 2D visual feedback, resolution and workspace limits, existence of obstacles in target workspace that block field of view and requirement of frequent cleaning during the operation due to the body fluids. Although by the help of rapidly developing technology high resolution cameras that are capable of providing stereoscopic visual feedback are started to be utilized in surgical operations nowadays, they are still not able to provide total permanent solutions to the mentioned difficulties [1-5]. In this point surgical navigation techniques have been emerged as an alternative solution for the visual feedback problems of minimally invasive surgical procedures. Basically surgical navigation relies on the virtual 3D visualization of the surgical workspace that is extracted and modelled by using classical medical imaging techniques. During the operations by the help of augmented reality and motion capture systems, motions of the surgical tools can be monitored and visualized inside this virtual environment. By this way surgeons can execute the operation more efficiently by relying on the enhanced virtual feedback with augmented reality.

In order to utilize efficient surgical navigation procedures during the surgeries, relationships between various reference systems inside the surgical workspace (patient, cameras, surgical tool references etc.) should be clearly and precisely described. In light of this many approaches were proposed inside the ongoing literature. Arun, Huang and Bolstein [6], introduced the calculation of transformation matrix that is required to determine the relationship between two distinct reference systems by using least squares methodology. In their works authors used the coordinates of known point sets with respect to both references. Hong and friends [7], introduced an effective point based registration by using landmark points taken from patient's body in order determine the transformation matrix between the virtual and real environment. Also in their later studies [8] they improved their methodology by the addition of landmark points inside the surgical workspace that were measured by the help of ultrasonic systems. This way they reduced the overall registration error. By using proposed algorithms same authors demonstrated successful results of surgical navigation in inner ear surgery [9], breast conserving surgery [10] and bone tumour resection [11].

Considering the applications of surgical navigation procedures in related literature, this study investigated the efficiency of utilizing analytical approach instead of numerical ones in point based registration by using OptiTrack V100R2 motion capture cameras (Figure 1).

Throughout the study, an analytical methodology that can be utilized to reveal the relationship between two distinct coordinate frames were introduced and tried on a rigid mockup target with known dimensions. At the end of the study acquired results were discussed with respect to the usability of mentioned methodology in navigation procedures.

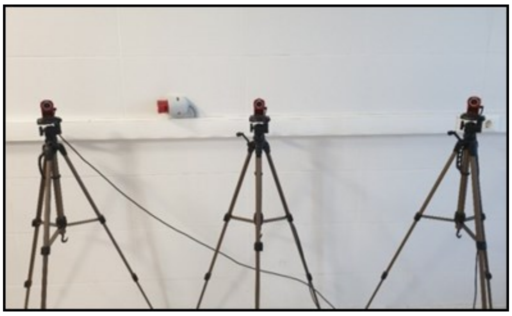

Figure 1. Optitrack Motion Capture Cameras

II. POINT BASED REGISTRATION

In any navigation applications, measurements that are acquired from the motion capture cameras defined with respect to the camera reference system (K). This reference system is the main property of the 3D motion capture workspace. Most of the operations are carried out within this system but on a sub local workspace (surgical target) that is defined with different reference system (Y) (Figure 2).

Related target (patient, body part etc.) was placed inside the motion capture workspace prior to the operation with a known location. Throughout the procedure in order to track the motions of the required tools, relationship between these two references should be identified in terms of a transformation matrix (${}^{K}_{Y}\mathbf{T}$)

A. Analytical Solution

Position of a random point that exits in workspace of the operation can be introduced by using Eq. (1).

$$\begin{bmatrix} {}^{K}\boldsymbol{\rho} \\ 1 \end{bmatrix} = {}^{K}_{Y}\mathbf{T} \begin{bmatrix} {}^{Y}\boldsymbol{\rho} \\ 1 \end{bmatrix} \tag{1}$$

In this equation ${}^{K}\boldsymbol{\rho} = \begin{bmatrix} {}^{K}\rho_x & {}^{K}\rho_y & {}^{K}\rho_z \end{bmatrix}^T$ and ${}^{Y}\boldsymbol{\rho} = \begin{bmatrix} {}^{Y}\rho_x & {}^{Y}\rho_y & {}^{Y}\rho_z \end{bmatrix}^T$ represents the position vectors of target random point with respect to the K and Y reference systems. Also transformation matrix consists of the rotation matrix ${}^{K}_{Y}\mathbf{R} = \begin{bmatrix} {}^{K}\hat{\mathbf{x}}_Y & {}^{K}\hat{\mathbf{y}}_Y & {}^{K}\hat{\mathbf{z}}_Y \end{bmatrix}$ that defines the orientation relation between reference systems and the translation vector between the origins of the references ${}^{K}\boldsymbol{\rho}_Y = \begin{bmatrix} {}^{K}\rho_{Yx} & {}^{K}\rho_{Yy} & {}^{K}\rho_{Yz} \end{bmatrix}^T$ (Eq. 2).

$${}^{K}_{Y}\mathbf{T} = \begin{bmatrix} {}^{K}_{Y}\mathbf{R} & {}^{K}\boldsymbol{\rho}_Y \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \tag{2}$$

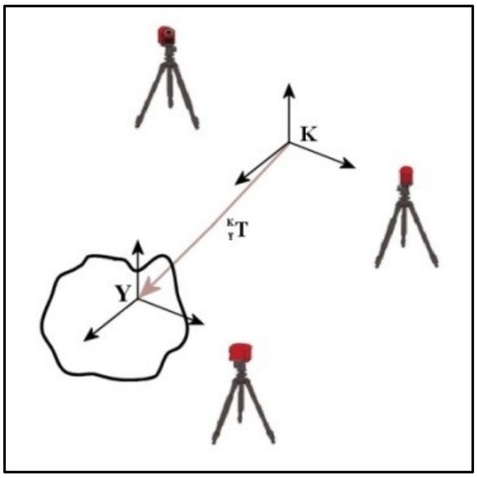

Figure 2. Motion Capture System Reference (K) and Local Reference (Y)

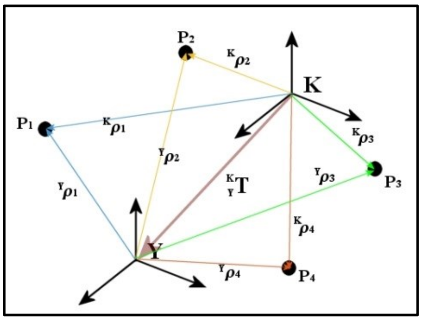

Figure 3. Construction of Equations to reveal Reference System Relation

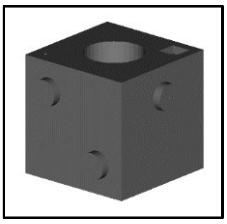

Figure 4. Model of Rigid Body Mockup with Landmark Points

As it can be seen in Eq. (2) in order to define the transformation matrix ${}^{K}_{Y}\mathbf{T}$, 12 parameters should be revealed (9 inside rotation matrix and 3 inside translation vector). Thus 12 independent equations should be formed. In order to construct required equations (Eq. 3), positions of 4 points located inside the workspace defined in both reference systems were sufficient ${}^{K}\boldsymbol{\rho}_i, {}^{Y}\boldsymbol{\rho}_i \;\; i = 1,2,3,4$ (Figure 3).

$$\begin{bmatrix} {}^{K}\boldsymbol{\rho}_i \\ 1 \end{bmatrix} = {}^{K}_{Y}\mathbf{T} \begin{bmatrix} {}^{Y}\boldsymbol{\rho}_i \\ 1 \end{bmatrix} \tag{3}$$

B. Registration Application

In order to verify the effectiveness of introduced analytical approach, a rigid body mockup with existing landmark points was designed and manufactured by using rapid prototyping system (Figure 4).

Knowing all of the structural dimensions of the mockup with respect to its own local coordinate frame (Y), it was placed into the workspace of the motion capture cameras following their proper calibration (Figure 5).

Figure 5. Model of Rigid Body Mockup within Motion Capture Workspace

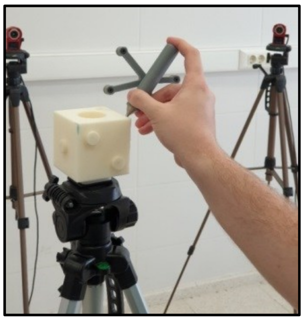

Figure 6. Measurement Procedure via Calibrated Stylus

During verification procedure by using a calibrated stylus, required position measurements were taken from the landmark points of the mockup (Figure 6) and using Eq. (3) ${}^{K}_{Y}\mathbf{T}$ transformation matrix that gives the relation between two reference systems were calculated.

At the end of the trials, in order to represent the effectiveness of the acquired transformation matrix in surgical navigation, measurements from the remaining landmark points were also taken with respect to the camera reference system and using calculated transformation matrix, corresponding local coordinate points were transformed to camera reference system by using Eq. (3). Later target registration error was calculated by comparing acquired results with real coordinates that are already known structurally. These results can be seen in table 1.

Transformation Matrix	$${}^{K}_{Y}\mathbf{T} = \begin{bmatrix} -0,676 & 0,057 & 0,738 & -16,047 \\ 0,051 & 0,991 & -0,043 & -126,088 \\ -0,752 & -0,002 & -0,691 & 29,897 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$		
Landmark Points (x y z)			
i	${}^{Y}\boldsymbol{\rho}_i$	${}^{K}\boldsymbol{\rho}_i$	${}^{K}\boldsymbol{\rho}_{i,real}$
1	(39,9 52,5 0,4)	(-39,7 -71,9 -0,6)	(-39,2 -72,3 -0,8)
2	(0,4 17,4 39,9)	(14,1 -110,4 1,8)	(13,3 -111,3 1,4)
3	(5,3 69,5 5,0)	(-11,9 -57,1 22,1)	(-12,8 -56,7 20,2)
4	(74,1 69,1 75,0)	(-6,8 -57,0 -77,9)	(-5,4 -58,6 -75,1)
5	(5,4 0,3 5,0)	(-16,0 -125,6 22,3)	(-16,0 -125,4 22,2)
Target Registration Error	RMS: 1.944 mm		

Table I. Registration Data

III. Results and Conclusions

When the acquired results were investigated from table 1, it can easily be seen that 3x3 rotation matrix ${}^{K}_{Y}\mathbf{R}$ inside the calculated transformation matrix ${}^{K}_{Y}\mathbf{T}$ is not orthogonal. As a result of this, registration distortions occured during the verification experiments that also increased the overall target registration error. It should be noted that introduced analytical methodology assumes the measurements taken from the motion capture cameras as exact values without having any errors. On the other hand, although they are calibrated, measurements taken by motion capture cameras still have some uncertainities due to their structural limitations (+/- 0.3 mm) in real life. Thus these results were expected.

In light of this although using introduced simple analytical approach by only considering 4 landmark points for surgical navigation is not sufficient for the operations that require sub milimeter precision, it can be utilized for coarser operations where the error can be tolerated.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this manuscript.

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