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A NEW APPROACH OF A LENGTH MEASURING SYSTEM IN ORTHOPEDICS USING A LASER PROBE

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Abstract: *This paper aims to present a new model of a length measuring system in orthopedics using a laser probe. A study of the current measuring methods in orthopedics revealed the need of an accurate, easy to use device, whose production or operating costs are not very high, and that doesn't expose both pacient and doctor to radiation. In order to achieve this requirements several researches upon different possible models were done. The devices are basen on coordinate metrology, that has reached a high level of accuracy. This paper will present one of the theoretical models, trying to define a certain point of the laser beam, so that in any moment, the doctor to be able to measure the distance between two points, thus achieving, for example, the length of a leg. When the best solution will be found, the device will be built and used both in clinical and intraoperative assesment.*

Key words: *length measuring, laser probe, coordinate measuring machine, orthopedics, leg length discrepancy.*

NOMENCLATURE

CATIA	Computer Aided Technical Innovations and Applications;
O_1A	homogenous rod;
G	weight;
L	length;
O_1O_2	vertical rod;
AB	laser beam;
ϕ	angle between OO_2 and O_1A;
v	speed;
ψ	angle between Ox and OB;
$\tilde{B}$	certain position of B;
$\mathcal{L}$	Lagrange function;
E	kinetic energy;
Π	potential.

1. INTRODUCTION

There is a constant need of measurement in our evryday life. Without even noticing we measure time, speed of a vechicle, temperature in a room, weight of our body, size of an object. For every measuring task, a specific device is being used [1]. In this paper, length measuring in orthopedics will be the task, and therefore a new length measuring system will be described. Researches have been made towards the existing measuring methods in orthopedics. Literature revealed that there are three major categories for assesing and measuring leg length discrepancy: clinical, imaging and intraoperative methods [2–5]. After analysing the advantages and disadvantages of each method, the need of a new length measuring system was found [6]. This system has the advantage, that it can measure with a higher precision, than other devices, it does not expose the pacient or the doctor to radiations, it is a non-invasive method, and can measure both at the bedside and on the operating table, the results being stored in the computer memory. In order to see if this is the best system to build, another theoretical devices have been studied [7]. One of them is a length measuring system with a laser probe that is further desribed in this article.

The major advantages of the system are the absence of contact between the device and the surgical field (patient), high accuracy in optimal conditions and ease of use. Among the disadvantages following can be mentioned: measurement accuracy variation according to the environment in which the laser beam is reflected and the angle of incidence (at small angles of incidence able the repeatability of measurements decreases) and high cost of production.

In order to increase the accuracy when the anatomical landmarks variate (periosteum, ligament, chondral tissue, fascia, etc.) some disposable "targets" were developed. These "targets" are round plastic pieces of various sizes that reflect uniformly the wavelength of 635 nm (red laser). They are attached to anatomical landmarks, allowing tracking, regardless of patient position.

This measuring system is further presented in the article.

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2. METHODS

A review of the literature was made, in order to see what methods are used for assesing leg length discrepancy. Three main methods were found, that are being used by doctors, both for clinical and intraoperative assesment [2–5]. A new length measuring system based on coordinate metrology was designed, in order to increase the measurement precison [6]. This new device has become the starting point for a PhD thesis, during which further research have been made. Based on a comparative analysis, which revealed the advantages and disatvantages of each measuring method, new theoretical models have been developed, so that in the end the best method to be choosed and built. The current paper presents a model designed in CATIA and its mathematical model and simulation. The potential advantages or disadvantages, together with further research direction are presented in the discussion section.

3. FUNDAMENTALS OF COORDINATE MEASURING USING NONCONTACT PROBES

Coordinate measuring machines are widely used for accurate dimensional mearurements of modern engineering objects. In order to cover different needs and specific requirements, a great number of probes have been developed. They can be divided in two main categories: contact and non-contact probes. Non contact probes are mainly used for flexible parts, that would be deformed if touched with a contact probe. High speed of point acquisition, high level of quality in results and the consequent time/cost reduction are the main advantages of this type of probes. Two categories of non contact probes can be distinguished: laser and vision [8–11].

- The most common laser technologies used in coordinate metrology, are those based on laser triangulation, due to its higher precision and lower cost. A laser beam is projected by a laser probe onto the surface of a part, and its position is then read by triangulation through a lens in the probe receptor. In order to achieve a high accuracy, the laser beam must be projected at the normal direction of the object [8, 12].
- Vision probes are very useful for high speed inspection, for very small 2D parts and for work pieces, that suffer frequent changes. A picture is digitized, so that the dimensions of the work piece can accurately be measured and evaluated in comparison to other models, by counting the pixels. This probes have the advantage, that they need to be calibrated only once [13 and 14].

4. GENERAL CHARACTERISTICS OF A LENGTH MEASURING SYSTEM IN ORTHOPEDICS USING A LASER PROBE

The length measuring system has the following components:

- a rod 1, which is fixed on its top side to stand 2, and has on its bottom end a disc 3, with a higher diameter, that doesn’t permit the sliding system 4 to fall down;
- stand 2 has 4 holes, that allow the system to be mounted on the ceiling;
- the sliding system 4 can move in vertical plane and rotate around rod 1;

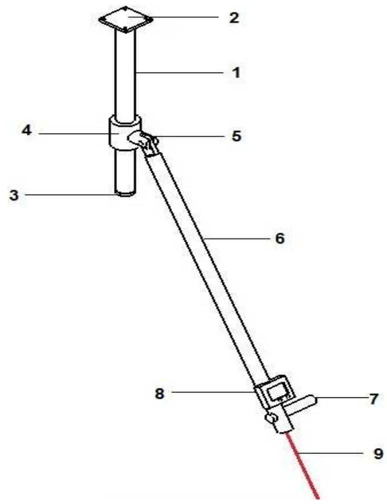

Fig. 1. Length measuring system using a laser probe.

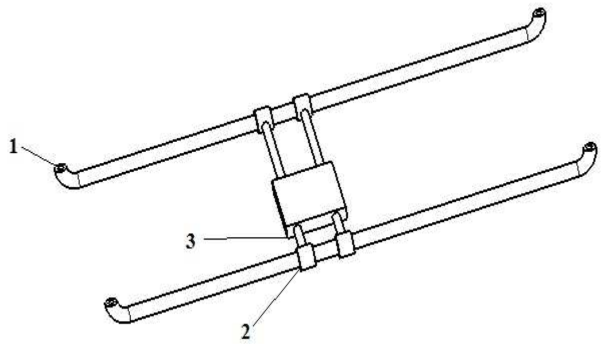

Fig. 2. Sliding system.

- a rod 5, which has a slot and is attached to the sliding system;
- a rod 6, which is articulated to the rod 5, through the slot, and can rotate in vertical plane;
- a handle 7 with sterilizable sleeve and integrated command button;
- a laser command device 8 with display;
- laser beam 9.

The entire system is mounted on the ceiling in the surgical room, or in cabinet, on a sliding system, like the one presented in Fig. 2.

The system consists of four rods (1, 3) fixed on the ceiling, that are used as rails for a sliding base (3). The base (3) serves as a mounting platform for the stand (2) from Fig. 1.

The positioning system has two degrees of freedom and its role is to settle the entire system in an optimal point relative to the measurement that will be performed. As soon as a fixed position is obtained, the measurements using laser telemetry system can be done.

It is worth mentioning that the system does not use any incremental rotation or translation transducer, the entire length calculation is made by using a fixed point where the source is, and based on the implemented algorithm from the processing unit.

The entire system is mounted on the ceiling in the surgical room, or in cabinet. When the doctor needs to measure a length on the pacients body, he simply takes the hadle 7, points the laser beam on the first bone landmark, pushes the button, than points the laser on the second landmark, pushes again the button, and so the laser device will calculate the distance between the two points, and display them. The calculated datas can be transfered via bluetooth to a computer ans stored in the pacients file. This measuring system has the advantage, that it can measure precisely the lengths on the human body, both clinical and intraoperative. The whole system can be covered with a sterile sleeve that can be thrown away after each surgery. Because nothing comes in contact with the human body, it reduces the risk of infections, and it has also the advantage, that it doesn't expose both pacient and doctor to radiations.

5. ANALYSIS OF A LENGTH MEASURING SYSTEM USING A LASER PROBE

For the convenience of analysis, the structure of the measuring system, can be simplified into a matematical model, as it can be seen in Fig. 3 [15].

A homogenous rod O_1A (weight $|\overline{G}| = 1.5g$ N and length $L = 2$ m), can slide on a vertical rod O_1O_2, so that point B, which represents the extremity of laser beam AB, to remain in the horizontal plane Oxy. Taking into consideration the purpose of the considered device, the movement of the rod O_1A and implicit of the point B will be stydied, so that the movement law to be known, which is necessary for the required experimental study. For the initial position, it is considered ϕ_0, the angle between the rod O_1A and Oz, the extremity B of laser beam having the speed $\overline{v}_0$, normal to the plane determined by O_1A and Oz axis.

The rod O_1A and laser beam AB, have the same direction, and this is defined by two parameters: the angles ϕ and ψ (the plane Oxy corresponds to the initial position). According to this parameters, the coordinates of a certain position $\tilde{B}$, of the extremity B are written:

$$\begin{aligned} \tilde{x} &= O_1\tilde{B}\sin\phi\cos\psi \\ \tilde{y} &= O_1\tilde{B}\sin\phi\sin\psi\,, \\ \tilde{z} &= \left(L - O_1\tilde{B}\right)\cos\phi \end{aligned} \tag{1}$$

which leads to the determination of the speed components of point $\tilde{B}$:

$$\left.\begin{aligned} \dot{\tilde{x}} &= O_1\tilde{B}\cdot\dot{\phi}\cdot\cos\phi\cos\psi - O_1\tilde{B}\cdot\dot{\psi}\cdot\sin\phi\sin\psi \\ \dot{\tilde{y}} &= O_1\tilde{B}\cdot\dot{\phi}\cdot\cos\phi\sin\psi + O_1\tilde{B}\cdot\dot{\psi}\cdot\sin\phi\cos\psi \\ \dot{\tilde{z}} &= -\left(\mathrm{L} - \mathrm{O}_1\tilde{B}\right)\cdot\dot{\phi}\cdot\sin\phi \end{aligned}\right\} \tag{2}$$

The differntial equations of movement can be determined with Lagrange equations second kind:

$$\frac{d}{dt}\left(\frac{\partial\mathcal{L}}{\partial\dot{q}_i}\right) - \frac{\partial\mathcal{L}}{\partial q_i} = 0, \quad q_i = \phi, \psi\,, \tag{3}$$

where $\mathcal{L}$ represents the Lagrange function

$$\mathcal{L} = E - \Pi\,, \tag{4}$$

which is equal to the sum between kinetic energy E and potential Π.

The kinetic energy of the rod can be written:

$$\begin{aligned} E &= \frac{1}{2}\int_{O_1A} v^2 dm = \\ &= \frac{1}{2}\int_0^L \left(\dot{\tilde{x}}^2 + \dot{\tilde{y}}^2 + \dot{\tilde{z}}^2\right)\cdot\frac{|\overline{G}|}{gL}\cdot d\left(O_1\tilde{B}\right) = \\ &= \frac{|\overline{G}|}{gL}\int_0^L \left[\begin{aligned} &O_1\tilde{B}^2\cdot\left(\dot{\phi}^2 + \dot{\psi}^2\cdot\sin^2\phi\right) + \\ &+ L^2\cdot\dot{\phi}^2\cdot\sin^2\phi - \\ &- 2L\cdot\dot{\phi}^2\cdot O_1\tilde{B}\cdot\sin^2\phi \end{aligned}\right] \cdot d\left(O_1\tilde{B}\right) = \\ &= \frac{|\overline{G}|L^2}{6g}\left(\dot{\phi}^2 + \dot{\psi}^2\cdot\sin^2\phi\right), \end{aligned} \tag{5}$$

and the potential:

$$\Pi = |\overline{G}|\cdot z_C = \frac{1}{2}|\overline{G}|\cdot L\cdot\cos\phi \tag{6}$$

The both terms of the Lagrange function (4) are known, therefore it can be written that:

$$\mathcal{L} = \frac{|\overline{G}|L^2}{6g}\left(\dot{\phi}^2 + \dot{\psi}^2\cdot\sin^2\phi\right) - \frac{1}{2}|\overline{G}|\cdot L\cos\phi \tag{7}$$

Based on Eqs. (3) and (4), the differential equations of the desired movement can also be written:

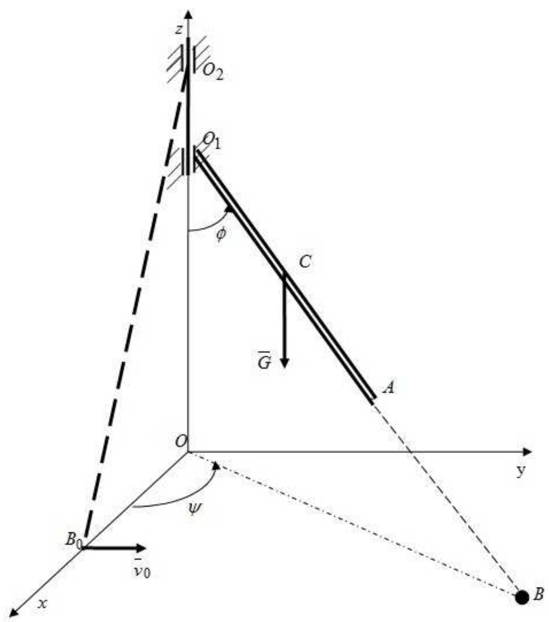

Fig. 3. Schematic representation of the length measuring system.

$$\left.\begin{array}{ll}\dfrac{\left|\overline{G}\right|L^2}{3g}\cdot\ddot{\phi}-\dfrac{\left|\overline{G}\right|L^2}{6g}\cdot\dot{\psi}^2\cdot\sin 2\phi-\dfrac{\left|\overline{G}\right|L}{2}\cdot\sin\phi=0 & (a)\\ \dfrac{d}{dt}\left(\dfrac{\left|\overline{G}\right|L^2}{3g}\cdot\dot{\psi}\cdot\sin^2\phi\right)=0 & (b)\end{array}\right\} \quad (8)$$

Taking into consideration the initial condition:

$$t=0\ \begin{cases}\phi=\phi_0\\ \psi=0\end{cases},\ B\begin{cases}\dot{x}_B=L\cdot\dot{\phi}\cdot\cos\phi_0\\ \dot{y}_B=L\cdot\dot{\psi}\cdot\sin\phi_0=v_0\end{cases} \quad (9)$$

and

$$\dot{\phi}=0;\ \dot{\psi}=\frac{v_0}{L\sin\phi_0}. \quad (10)$$

it results that:

$$\dot{\psi}\cdot\sin^2\phi=\frac{v_0}{L\sin\phi_0}\cdot\sin^2\phi_0 \quad \text{or}$$

$$\dot{\psi}=\frac{v_0\cdot\sin\phi_0}{L\sin^2\phi}\cdot\sin\phi_0\,, \quad (11)$$

Replacing (11) in (8a) and amplifing with $2\dot{\phi}$ and integrating, taking into consideration the initial condition (9), (10), the following equation is obtained:

$$\dot{\phi}^2+\frac{1}{\sin^2\phi}\cdot\frac{v_0^2}{L^2}\cdot\sin^2\phi_0+\frac{3g}{L}\cdot\cos\phi=\frac{v_0^2}{L^2}+\frac{3g}{L}\cdot\cos\phi_0 \quad (12)$$

which allows the writing of the solution, depending on a third grade polynom $Q_3(\cos\phi)$, respectively:

$$\dot{\phi}=\frac{1}{L\sin\phi}\cdot\sqrt{Q_3(\cos\phi)}\,. \quad (13)$$

The polynom Q_3 has the following form:

$$Q_3(\cos\phi)=(\cos\phi-\cos\phi_0)\cdot\left[3gL(\cos^2\phi-1)-v_0^2(\cos\phi+\cos\phi_0)\right], \quad (14)$$

with the roots:

$$\left.\begin{array}{l}\cos\phi_1=\cos\phi_0\\ \cos\phi_2=\dfrac{v_0^2-\sqrt{v_0^4+12v_0^2Lg\cos\phi_0+36L^2g^2}}{6Lg}\\ \cos\phi_3=\dfrac{v_0^2+\sqrt{v_0^4+12v_0^2Lg\cos\phi_0+36L^2g^2}}{6Lg}\end{array}\right\} \quad (15)$$

Analysing the roots, it is found that the solution ϕ_2 is always possible, because $-1\le\cos\phi_2<0$, whatever the angle ϕ_0 would be, while the solution ϕ_3 has no meaning, because $\cos\phi_3>1$.

It is considered, that the movement is possible for $\dot{\phi}^2>0$, which implies $Q_3(\cos\phi)>0$.

The following equation is obtained:

$$\phi\in\left[\begin{array}{l}\phi_0,\phi_2=\\ =\arccos\dfrac{v_0^2-\sqrt{v_0^4+12v_0^2Lg\cos\phi_0+36L^2g^2}}{6Lg}\end{array}\right] \quad (16)$$

From the equation (8) results that the extremity B of the laser beam describes the Oxy plane, with a constant areolar speed $\Omega=\dot{\psi}\cdot(OB)^2$. The movement of the rod, and implicitly of the laser beam is possible in following intervals: $[\phi_0,\phi_2]$ or $[\phi_2,\phi_0]$, and point B describes in Oxy plane a curve situated inside a circural crown, tangent to the circles with radius $L\sin\phi_0$ and $L\sin\phi_2$ [15].

For the considered calues, a numerical solution will be further presented.

6. SIMULATION EXPERIMENT OF THE STUDIED MODEL

Considering the weight $\left|\overline{G}\right|=1.5g$ N, the length $L=2$ m, the initial speed $v_0=0.1$ m/s, (which takes into account the movement of the laser beam end through an external action), the gravitational acceleration $g=9.81\,\text{m/s}^2$, and the initial position $\phi_0=\pi/12$, when this is considered constant, following graphs of the angular velocity $\dot{\phi}$, are obtainted. They correspond to the cases from Table 1.

Table 1

The cases for the angular velocity $\dot{\phi}$

Case	The initial position expressed through the angles ϕ_0 and ϕ	Figure
1.	$\phi_0=\pi/12$ – determinated ϕ – variabile in range $[-\pi,\pi]$	Fig. 4 – according to Eq. (13)
2.	Both angles ϕ_0, and ϕ vary in $[-\pi,\pi]$ interval with 0.2	Fig. 5 – according to Eq. (13)

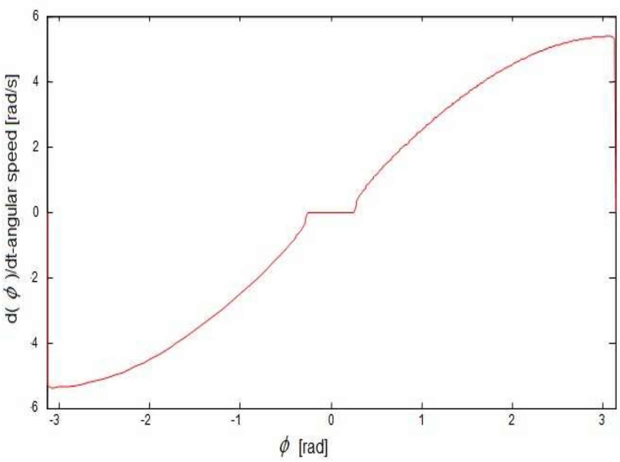

Fig. 4. Case 1: the variation of angular speed for the initial position. $\phi_0=\pi/12$.

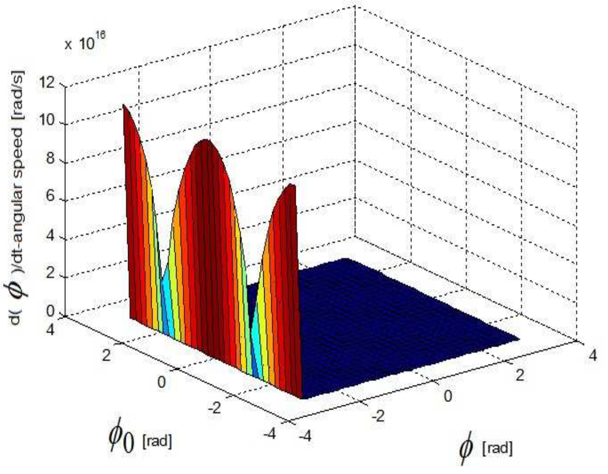

Fig. 5. Case 2: variation of the angular speed for ϕ_0 and ϕ.

Knowing the variation of the angular speed $\dot{\phi}$ depending on ϕ, as well the posibility of drawing the variation of this two parameters in a certain period of time (Figs. 6 and 7) it is possible to identify the laser beam position, for each moment of the considered time frame. The position of the laser beam (point *B*) is determined by ϕ and ψ conf. (11)) through (1), where $O_1\tilde{B} = L$.

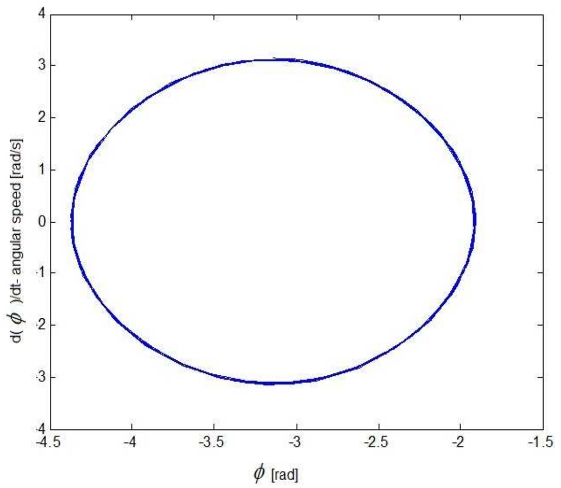

Fig. 6. Phase plane ($\phi \in [-\pi, \pi]$ $t \in [0, 20]$).

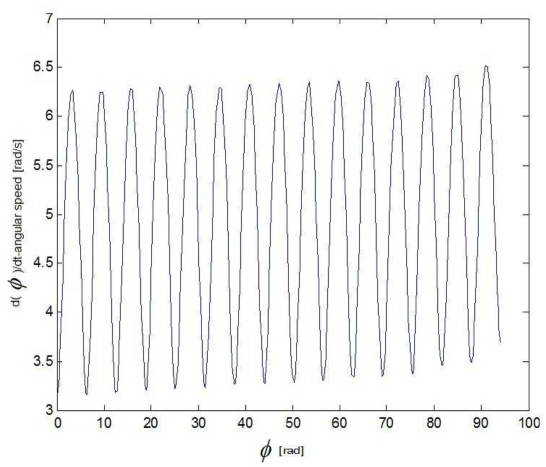

Fig. 7. Phase plane ($\phi \in [0, \pi]$, $t \in [0, 20]$ [s]).

7. DISCUSSION

The proposed model was analysed based on a mathematical model and an experimental simulation. The purpose of the research, was to identify a certain position of the laser beam extremity. In order to achieve this requirement, the Lagrange equations second kind are being used, taking into consideration all the implied aspects [15]. For the simulation experiment and in order to obtain the necessary results for describing the studied phenomena, for the indicated construction values, MATLAB and CATIA were used. In the end, it is for certain known which are the coordinates of any laser beam point.

8. CONCLUSIONS

The present paper aims to present a new model of a length measuring system using a laser probe, with aplicability in orthopedics. After analysing the existing measuring methods used by doctors, the need of a new system is identified. A new model is designed [6], but in order to be sure, that this is the best solution to be built, another researches are made. In this paper a new device was presented, together with the analysis of its dynamic, based on an adequate mathematic model, so that the position of the laser beam extremity to be identified, which corresponds to the purpose of the designed system. The simulated experiment revealed the position of the laser beam extremity, so that for a measuring task, it is always known the coordinates of a measuring point, thus being able to measure any distance on a human body.

The major advantages of the system are the absence of contact between the device and the surgical field (patient), high accuracy in optimal conditions and ease of use. Among the disadvantages following can be mentioned: measurement accuracy variation according to the environment in which the laser beam is reflected and the angle of incidence (at small angles of incidence able the repeatability of measurements decreases) and high cost of production.

Further researches will be made, and the best solution will be built and tested, first in a laboratory, and than for clinical assesment.

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