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Active Tracking Control between a Bio-robot and a Human Subject

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Abstract—**This paper discusses the tracking algorithms and approach used to control the Tracking Fluoroscope System. It is a mobile platform equipped with an on-board fluoroscope system to perform real-time imaging of human joints in motion: ankles, knees and hips. In order to record the natural and uninterrupted joint motion, the person has to be able to walk freely while being followed by the robot. It requires independent tracking of the position and orientation of the body with respect to the platform as well as joint positions with respect to the trunk of the body. This paper investigates the problem of tracking position and orientation of a walking person with respect to the following robotic platform.**

I. Introduction

THE Tracking Fluoroscope System (TFS) is an autonomous mobile robotic platform equipped with omnidirectional wheels, and two pairs of horizontal and vertical linear stages carrying a real-time fluoroscope system [1, 2] shown in Fig 1.

Fig. 1. Tracking Fluoroscope System.

Current fluoroscope systems are usually in a form of a C-arm frame [3]. The position of the source and receiver is generally fixed with respect to ground and patient allowing only adjustment the height of such a system to meet the height of a patient shown in Fig 2. Unfortunately, it does not resemble natural walking or show the full dynamics of the joint. Hence, it becomes harder to design a prosthesis that would perform well under real conditions.

Fig. 2. An example of traditional knee bend for analyzing human joint.

The current prototype design is an attempt to overcome those limitations, however it brings new challenges. One of them is to provide accurate, real-time tracking of body position with respect to the frame of the platform. It senses the x-y position and orientation and keeps it within limits as in Fig 3.

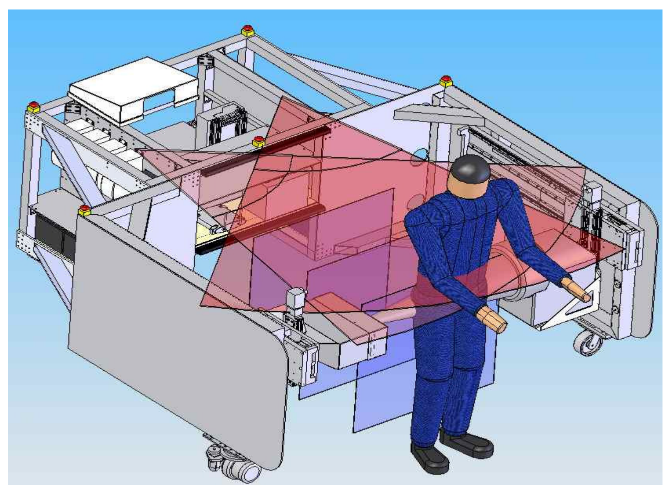

Fig. 3. Human model presented in the workspace of the robot.

This paper describes the study of tracking a walking person being followed by a robotic platform and is organized as follows. Chapter II presents detailed information on the Tracking Fluoroscope System. Chapter III presents the challenges and previous findings on tracking. Chapter IV shows current approach and results. Finally, chapter V describes conclusions and future work.

II. System description

TFS consists of several subsystems: main drives, joint tracking drives, main controller, image acquisition system, safety system, power supply, fluoroscope and sensing

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system. Those components are attached to a light aluminum frame.

The main drive system includes: DC omnidirectional motors in wheel drives equipped with encoders and brakes for wheels and potentiometers for steering, servo amplifiers, and additional casters.

The joint tracking drive subsystem consists of two pairs of linear horizontal and vertical stages equipped with analog encoders and brakes and AC digital servo amplifiers.

The image acquisition system is responsible for processing, storing and sending the x-ray video feedback as well as providing a control signal to the control computer.

The main controller is an industry standard National Instruments PXI PC. It gathers the signals from the image acquisition and laser scanning, processes it, and provides steering signals for all drives.

The safety system is responsible for handling possible dangerous situations that could hurt the patient or damage the hardware. It consists of ultrasonic sensors, bumper switches, radio controlled and hardware E-stops, and a programmable logic controller. Some of the safety functions are directly embedded into other systems like drives and laser scanners.

The power is supplied from onboard 12V batteries gathered in parallel-serial connection to provide 24V. Overall, the power bus provides 3 ranges of voltage: 12VDC, 24VDC and 110AC with appropriate DC/DC, AC/DC converters and fuses/breakers.

The X-ray is a commercially available fluoroscopy system redesigned to meet the requirement of the mobile platform. It receives power from the onboard bus and feeds the image acquisition system.

TFS is equipped with a pair of 2D laser scanners. It can scan the surrounding environment at frequencies ranging from 200 to 500Hz with an angular range of 70°. It provides three kinds of data: angle, distance and remission value. The first two allow for processing the data in Cartesian coordinate frame. The remission value is used to filter real data - real points from artifacts.

The frame is built of light weight bolted and welded parts. It was designed to be firm enough to hold the moving parts, prevent vibrations and small enough to be aesthetic and possible to travel through doors if necessary. In order to make it possible, the right and left parts (wings of the platform are detachable.

III. Problem Description

This paper focuses on the goal of tracking position and orientation of a human during normal walk. It brings several problems and questions.

The first thing is to define position and orientation with respect to a human subject and mobile platform. Position of the body is considered to be a Cartesian position of the center of the body as viewed from the top (Fig. 4). The center of the body is considered as the center of area of the top projection.

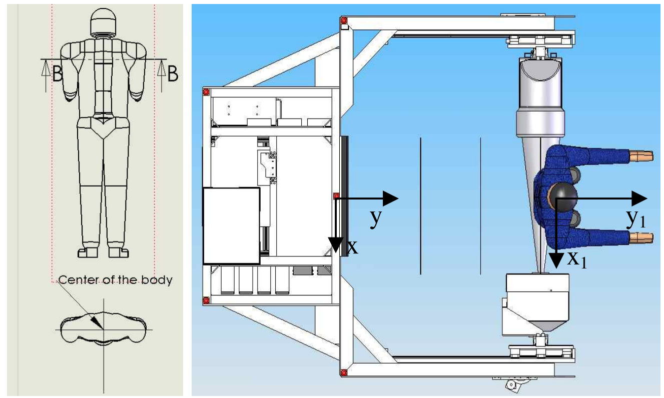

Fig. 4. Coordinate frames. Left image - view of the scanned area, right image - coordinate frames of the object and cart.

The orientation of the body trunk is regarded as an angle between the object and the robot plane of symmetry. It is simply the heading angle with respect to the mobile platform. It does not depend on the head orientation or hand movements.

The main goal of the tracking problem is to keep the patient within the range of motion of the joint tracking drives. Hence, it is not necessary to have a steady state error equal to zero. It is more important to be able to smoothly follow the person even at the the cost of temporarily increasing error.

The first approach to this problem was a 1D laser range scanner described in [2, 4]. The scanner mounted in the middle of the frame was pointed at person's trunk. It was verified that such a solution is good enough to precisely and in a stable manner track a person walking a straight path away or toward the robot. Obviously it does not allow for a change in heading.

Based on this experience it was decided to equip the platform with a pair of 2D SICK LMS 400 laser scanners as shown in Fig. 5. They provide the necessary angular (70°) range and distance range (0.7m to 3m) as well as statistical error (1 sigma) range (3-9 mm) in ambient room conditions.

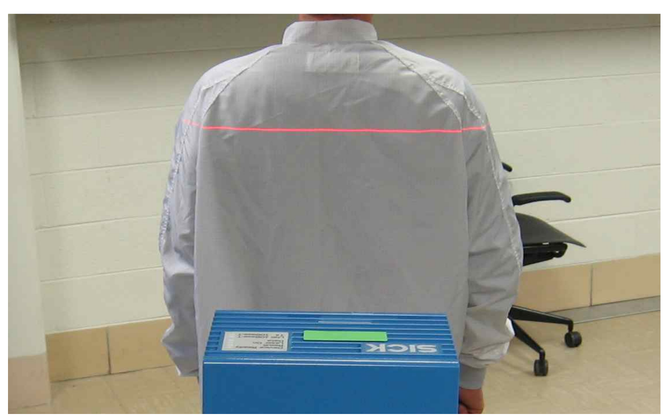

Fig. 5. LMS 400 scanning the back of a person. The red line represents the actual line of scan

One of the most important issues was how to position the scanners on the cart, so the readings are stable and repeatable for a walking person.

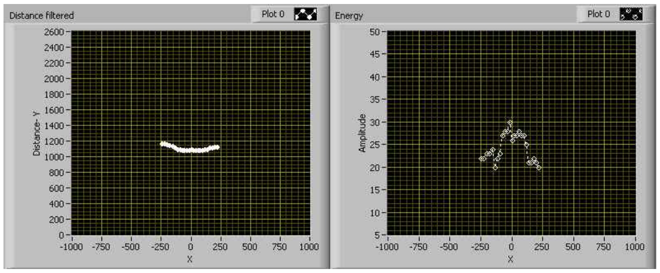

Fig. 6. An example of a human torso seen by the scanner. Cartesian position on the left and remission values on the right

The most difficult problem however, was to conclude what is the orientation of the object. The output of the scanner provides a set of data that includes distance, remission and angle for each point on the line of view of the scanner (Fig. 6.). The number of the points is custom but affects the quality of the signal and speed. The quality of the data decreases with the number of points and speed. The quality is considered in terms of the expected error. Based on these data, three values are to be obtained: x-position, y-position and orientation angle α.

IV. APPROACH AND RESULTS

The first problem to consider was the positioning of the scanners. Due to the fact of the required minimum distance between the object and scanner it was necessary to place it above the top of the platform - 1m above the ground. This means that for the majority of the population the lasers have to be pointed out at the region between the waist and top of the head. During normal walking a person's arms are in motion. The degree of motion may vary drastically from person to person. The top projection of the neck and head does not provide enough information to conclude the orientation. That leaves only the top part of the region between elbows and shoulders as in Fig. 5 and 7. It also requires height adjustability of the scanner for different patients. Another way to compensate for different height could be to provide adjustable vertical angle - tilt. However, during walking, the distance to the object may vary due to nonlinearities and hard to predict body curve. During motion the angle at which the body is scanned is changing, the vertical curve of the body is not covered evenly, the remission is not constant and the number of scanned points can vary as well. Hence, it was decided to use two scanners symmetrically positioned with respect to the object at the same height. It is assumed that the maximum change of the orientation angle of the person is relatively small ±15°. In a case of a higher value the robot should perform an emergency shutdown due to large tracking error. This also puts a limit on the dynamics of the person. Both scanners point at the person when standing in the middle of the joint tracking workspace as in Fig 7. It was tested that the minimum data update frequency required for smooth operation of the platform is 20Hz [5]. The scanner can work at the minimum rate of 200Hz and the data can be acquired in real time only when using an Ethernet TCP/IP connection. The other available port, RS232, cannot provide data transfer at that rate. The processing PC has to work in real time in order to receive the data in a timely manner. It was decided to perform all processing using the real time LabView environment.

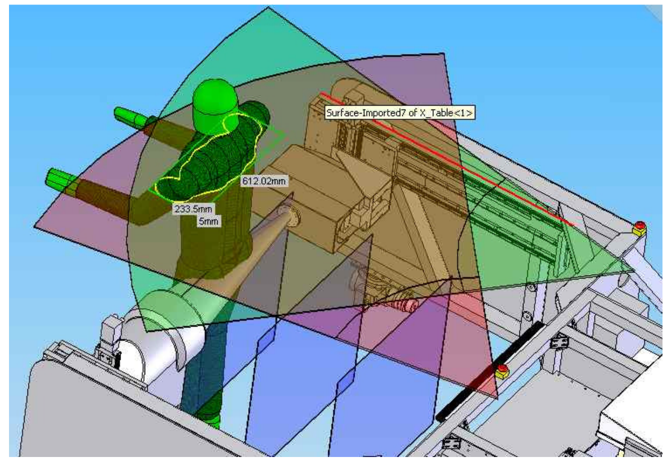

Fig. 7. An example of scanners pointing at model's shoulders, maximum distance

In order to obtain the position of the body, the data has to be filtered first and then processed. Based on the acquired data it was observed that the artifacts may have remission value up to 12-13%. Then the threshold was set to be 15%. All data below this threshold are removed from the set, effectively decreasing the number of body profile points. In order to provide uniform repeatable results, each person is required to wear a white lab coat. It allows for easier separation of real data from artifacts. The internal scanner algorithms allow for filtering using the median filter and average value. The average value calculation is effectively slowing down the data transfer. The median value does not cause this problem. Both algorithms are turned on and the data coming to the processing PC is already pre-filtered. After receiving the measurements, applying the threshold and calculating the Cartesian position, the curve of the body looks as in Fig. 6.

The position of the person is found by calculating the center of the area for all data points. The most difficult problem is to obtain the change in rotation.

Several algorithms are considered to obtain the orientation for tracking. The first one is linear regression. The curve of the body for the same person, seen by the scanner can be a part of an ellipse or an arc. Even if considering a small motion of the arms just below the shoulders, the point path does not change significantly. Hence, the linear approximation would not either. The linear regression could be used to obtain orientation of the body [6].

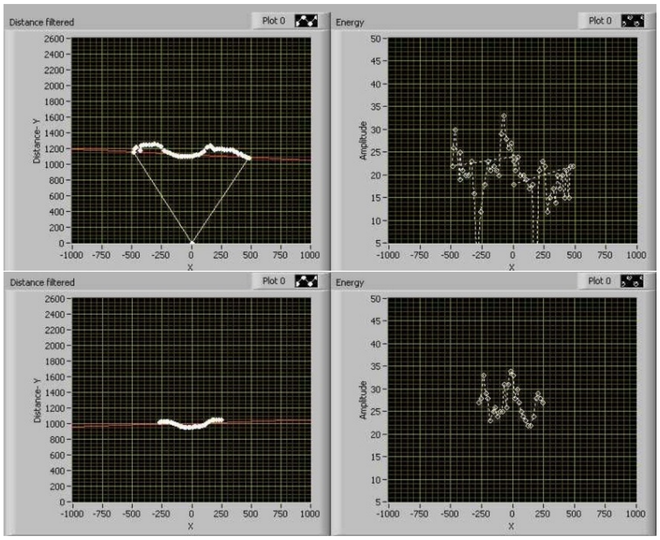

Fig. 8. Data before and after filtering. Top - unfiltered, bottom – filtered

The body curve can then be approximated using the equation:

$$y = ax + b$$
$$a = \tan(\alpha) \quad . \tag{1}$$

The data available for processing is x- y values of the point of the curve. Hence, a system of equations can be formed as follows:

$$\begin{bmatrix} x_1 & 1 \\ \vdots & \vdots \\ x_i & 1 \\ \vdots & \vdots \\ x_N & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_N \end{bmatrix}, \tag{2}$$

where N - number of points.
Therefore, the solution can be obtained as:

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} x_1 & 1 \\ \vdots & \vdots \\ x_i & 1 \\ \vdots & \vdots \\ x_N & 1 \end{bmatrix}^{+} \begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_N \end{bmatrix}, \tag{3}$$

the plus sign denotes a pseudoinverse. The angle is easily obtained:

$$\alpha = \tan(a)^{-1} . \tag{4}$$

The results of the above calculations are shown in the Fig. 8 and 9. The continuous red line represents the approximation from eq. 1. Since the real rank of the inverted matrix is 2, no degree of freedom can be dropped. It means that in a case of outliers in the data set, the solution can be distorted. The pseudoinverse was found using singular value decomposition. An example of the resulting line is shown in Fig. 10.

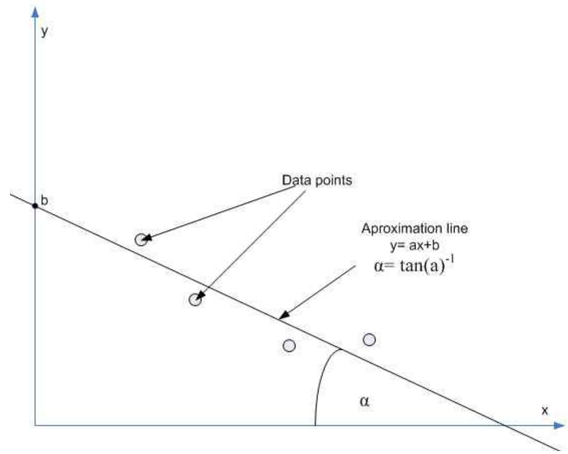

Fig. 9. Linear regression line

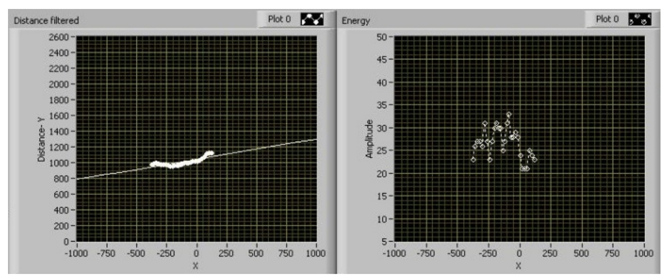

Fig. 10. Linear regression applied to data points. Points come from the laser scanner; line is built based on the linear regression

Another way to obtain the orientation is to find the principal axis [7]. For a symmetrical object it coincidences with the symmetry axis and its position and orientation change accordingly. In order to do that, the center of the area has to be found first, and it is done as follows:

$$x_c = \frac{\sum_{i=1,N} x_i}{N}$$
$$y_c = \frac{\sum_{i=1,N} y_i}{N} \quad , \tag{5}$$

where, x_c, y_c- coordinates of the center of area. The points are treated as small unit areas for simplicity. Next all data points are expressed in a coordinate frame attached to the center of the gravity.

$$x_{inew} = x_i - x_c$$
$$y_{inew} = y_i - y_c \tag{6}$$

Knowing that, all moments of area are found:

$$I_x = \sum_{i=1,N} y_{inew}^2$$
$$I_y = \sum_{i=1,N} x_{inew}^2 \qquad . \qquad (7)$$
$$I_{xy} = \sum_{i=1,N} x_{inew} y_{inew}$$

I_x,I_y,I_{xy}- second moments of area about axis x, y and product moment of area.

The coordinate system can be rotated in order to align the coordinate axis with the principal axis. When it happens the product moment is zero, hence the angle can be calculated as:

$$\alpha = -\frac{1}{2}\arctan\frac{2I_{xy}}{I_x - I_y}. \qquad (8)$$

A situation in which moments of area are equal resulting in dividing by zero can only happen in a case of a malfunction and is considered as a reason for an emergency shutdown. An example of the resulting orientation line is shown in Fig. 10.

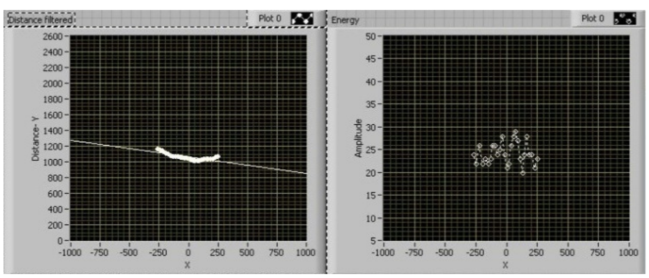

Fig. 11. Orientation line obtained through second area moment method

Both methods were tested using the same the subject and the result were consistent. In order to do that an interface panel was developed using LabView environment. It allowed for instant change between algorithms and visual presentation of the results. The sample change in angle is presented in the following Table1. It shows the relative angle of the person being scanned with respect to the scanner coordinate frame obtained using two different methods. The results were obtained for different body positions. Each row shows two angle values obtained for the same body orientation.

Table 1. Orientation angle obtained using two different methods. Units in degrees

Linear regression	Moment or area
0.5	**0.6**
-8	**-9**
23	**22**
-22	**-21**

Another approach is a hybrid method. Due to the motion, remission threshold and an uneven surface of the measured object every scan brings a set of measurement of different points. The curve of the body is preserved but based on different data points. This leads to the idea of normalizing the data. Each scan represents a rotated and translated image of the same body curve. Thus it is beneficial to set a standard curve. It can be done by placing the person in a predefined position to obtain the reference curve. Then regular scanning can be performed. After every scan the data points are being matched to the reference set. Next step is to use linear regression, principal axes, or any other different method to obtain the orientation and position based on the new position of the reference curve. The details of the matching part of this method are under development.

The change of the orientation is assumed to be smooth, therefore prediction methods are also considered to be used in this research.

All above algorithms were tested using a single scanner and a stationary person performing only turns and simulating walking. In order to validate the describe algorithms more in depth analysis is required. It is necessary to perform an experiment with a slowly walking person and evaluate the stationary results through the following criteria: the maximum range of turn a person can safely perform, the effectiveness of the algorithm depending on the height, the curve of the scanned part, conditions necessary to perform an emergency shutdown and handling the situations in which the results from one scanner contradicts the second one. A solution to the last case could be building a body section model based on both scanners. In such a case the redundancy problem is limited to a proper alignment and calibration of both scanners

After obtaining the position and orientation of the patient an appropriate controller is necessary to drive the position error to zero. The desirable stand-off distance of the person should be constant during the motion. Hence, the error function could be defined as $\boldsymbol{e}(t)=\boldsymbol{d}(\boldsymbol{t})-\boldsymbol{D}$, where $\boldsymbol{d}$ is the actual distance and $\boldsymbol{D}$ is the desired distance. In general, the control input is the platform velocity $\boldsymbol{u}=\boldsymbol{dd/dt}$ therefore, a simple proportional control law can be given as:

$$u(t) = Ke(t)\,, \qquad (9)$$

where K is a constant gain. The control of the orientation angle can be approached in a similar fashion. A more detailed discussion can be found in [5].

V. Conclusions

The problem of tracking a walking person was presented and the possible solutions discussed. The experiments were conducted on a real person and it was shown that the described methods could be used in the next phase of the project. Both methods gave consistent results. They were evaluated based on the image of the curve of the body since there was not a standard reference method to obtain solutions. The problem of positioning the laser and filtering its reading were discussed. The most effective area of the body for scanning was located. The readings were filtered using median filter and remission threshold.

In the next step the described approach will be applied to a walking person being followed by the cart. Several problems will need to be addressed. It includes the cooperation between two laser scanners, finding the maximum safe angle of turn and evaluation of the whole tracking system.

VI. References

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