A REPOSITIONING METHOD OF C-ARM USING MOTION CAPTURE ON THE VIRTUAL REALITY PLATFORM

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Abstract - Currently, the C-Arm X-ray system (C-Arm) is a manually (or partially automated) maneuvered device used to take medical images such as MRI and X-rays during surgery in the operation room. The primary goal of this research is to identify and test a framework for facilitating the repositioning of the C-Arm without hardware modification in an operating room. This will be accomplished by enhancing a data acquisition process using the Vicon motion capture system (Vicon) and virtual reality (VR)-based platforms, as well as improving the repositioning process in C-Arm using image matching techniques such as automatic target acquisition (ATA). Using MATLAB/Simulink the C-Arm will have the ability to acquire data acquisition as well as signal processing to adjust each component of the C-Arm.

Index Terms - Automatic Target Acquisition,MATLAB/Simulink,Vicon Motion Capture, Virtual Reality Based Platforms

I. FRAME OF REFERENCE

One of the most significant advancements in radiology was the ability to take radiographs during surgery. With this ability, surgeons were able to perform surgical procedures which they had previously known to be impossible. In recent years, the C-Arm X-Ray systems (C-Arm) shown in Fig. 1 has become one of the most popular portable X-ray machines for surgeons. The C-Arm has become so popular because of its five degrees of freedom maneuverability. These five degrees of freedom include translation in the vertical, translation in the horizontal, rotation about the vertical axis, rotation about the horizontal axis, and orbital motion of the C-Orbital. This has given surgeons and X-ray technicians the ability to take images of the human body during surgery at virtually any angle. However, as practical as the C-Arm is, it still has some shortcomings. C-Arms are still maneuvered manually during surgery and require a skilled X-ray technician to operate. The manual maneuvering of the C-Arm is sufficient most of the time; however, complications with accuracy arise during sensitive procedures.



Fig.1: Current C-Arm configuration [1]

Certain surgical procedures require large equipment and the interaction of multiple operators. In those surgeries where large equipment is used, the C-Arm is rolled off to the side to allow for more room. The problem arises when the C-Arm must be repositioned back to its original reference with respect to the patient for image taking and validations of the surgical procedure and maneuvers. This repositioning of the C-Arm oftentimes becomes difficult, inaccurate, or a repetitive process. At times, multiple X-rays are taken to validate the repositioning of the C-Arm, exposing patients, surgeons, and X-ray technicians to unnecessary radiation. Furthermore, every minute that passes, because of repositioning the C-Arm, will increase the cost of surgery. The cost includes the payment of the X-ray technician and rent of the operation room and equipment. In addition to the cost, the longer a patient is exposed to the environment through surgery, the risk of infection increases for that person, meaning that if the repositioning time of the C-Arm was reduced, the risk of infection is also directly reduced.

Manufacturers of the C-Arm are fully aware of the shortcomings of their design during certain surgical procedures and have made attempts to develop a C-Arm that can maneuver autonomously; however, the addition and development of the new technology drives the price of the C-Arm up significantly to where the benefits are no longer cost effective. In other words, hospitals are not willing to purchase a more expensive C-Arm if they have a perfectly functioning C-Arm in their operation rooms capable of performing sufficiently in most of cases. The best solution would be to modify existing C-Arms to be able to maneuver automatically and more accurately.

II. LITERATURE REVIEW

It is difficult to place the C-Arm in such a way that an area of interest falls within the imaging range. Because

of this, multiple trials of readjustments have to be made by experienced operators. However, imaging methods have been developed for areas of interest that lie within the border of radiographs. In this method, an image can be re-centered by choosing a new location to be the image center; with the users input, the edge-lying area of interest can be automatically moved to the center of the image [2]. This method of automated positioning and repositioning has been made through imaging processing; however, this current repositioning method is not fully automatic as it requires user input for determination of the desired region. In other words, as it currently stands, the C-Arm is capable of moving on its own, but it still needs external input from a technician to approximate or pinpoint the desired center point.

Considerable efforts have been made to improve the repositioning capabilities of the C-Arm by optimizing the use of the computed tomography (CT) and C-Arm imaging with external tracking systems. To alleviate some of the drawbacks faced by these systems, a variety of Camera-Augmented Mobile C-Arm (CAMC) solutions have been proposed to calibrate the C-Arm's projection geometry online by attaching a camera and image intensifier and detector to the mobile C-Arm. The integrated CAMC system makes it possible to enable intraoperative navigation without an external tracking system; however, an additional procedure is required for the setup of the CAMC as well as its associated calibration, which needs additional time and professional skills [3].

Distortions are also present in both optical video camera and X-ray imaging in some of the current developments. These systems require calibration at every orientation for more exact distortion rectifications. Distortions requiring corrections not as urgently depend on models and precomputed look-up tables [3]. In addition, these systems lead to inaccuracy due to a slightly reduced distance between the radiation source and image intensifier, creating more problems that require further handling by well-trained operators for additional calibration processes.Therefore, in this proposed project, the repositioning method using Vicon motion capture and image matching techniques has been proposed to improve the accuracy and the setup time without the hardware modification of the C-Arm. This methodology, which consists of virtual reality (VR)-based analytical models and repositioning techniques, can be used for positioning as well as repositioning of the C-Arm in an operating room. The kinematics-modeling algorithm, which is implemented in the VR-based platform, is used for estimating the joint movements of the C-arm from known position vectors and orientation angles of the end-effector and vice-versa. This algorithm enables us to create 3D vector points and reference data which will be used in the image matching process for the repositioning of C-Arm systems.

III. DESIGN AND METHODS

To fully develop a system to upgrade any C-Arm to operate with motion capture technology, two objectives must be met first. The primary objective is to construct and fully erect a physical C-Arm prototype accompanied by a virtual model created using computer aided design (CAD) software. The secondary objective, which falls into future work, is to implement Vicon motion capture technology as shown in Fig. 2to move the miniature C-Arm into desired locations. By integrating the automatic target detection system, the C-arm will be able to relocate itself automatically.

A.Basic Concepts of Target Acquisition

Using an optical marker-based system, the position of a target may be found in 3D space by using cameras positioned at any differing angles and distances. By tagging the target with a detectable marker within the field of view of the cameras, each camera can develop a 2D image in which the position of the marker is known. Combining the known orientation of the cameras with the marker's position in each of the 2D images, a 3D vector from the camera to the marked target can be established. With this, the instantaneous position of the target may be determined [5].

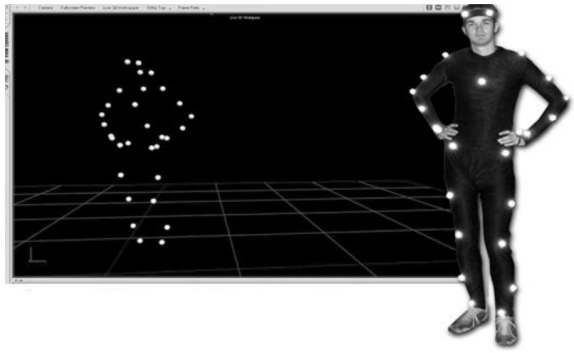


Fig.2: Example of Vicon motion capture technology [4]

To relocate the target back to a previous position, the use of global coordinate system (GCS) and local coordinate systems (LCS) could be implemented. An LCS can be assigned to the target, and the position of a camera may be used for the GCS, allowing the orientation of the target to be referenced to the camera. Using Euler angles, any rotation by the LCS can be represented by three rotations about the axes of the GCS. Along with the changes in the coordinates of the origin of the LCS, a complete map of all possible changes in orientation between the target and camera can be found. In this manner, the target could easily be repositioned to any previous orientation [5].

The VR-based platform creates the reference points which will be used as the GCS in the repositioning process. The position of each marker point can be represented by using the rotation matrix based on Euler angles. In case of a 3D rotation at which a

rotation of θ around the z axis, followed by a rotation of ψ around the x axis, the rotation matrix R can be expressed by

$$R = \begin{bmatrix} \cos\theta & -\sin\theta\sin\psi & \sin\theta\sin\psi \\ \sin\theta & \cos\theta\cos\psi & -\sin\theta\sin\psi \\ 0 & \sin\psi & \cos\psi \end{bmatrix} \quad (1)$$

To perform the automatic target acquisition process, the pan and tilt angles for the Vicon camera are expressed as a function of the coordinates (x_t, y_t, z_t) as [6]

$$\theta = \sin^{-1} \frac{x_t}{\sqrt{x_t^2 + y_t^2}} \quad (2)$$

$$\delta = \cos^{-1} \frac{\sqrt{x_t^2 + y_t^2}}{\sqrt{x_t^2 + y_t^2 + (Z_c - Z_t)^2}} \quad (3)$$

where the subscripts ' t ' and ' c ' represent the coordinates of target and camera, respectively.
The schematic illustrations of the pan and tilt angles are represented in Fig. 3. The iterative tracking algorithm can be examined by using the series of captured images obtained from the VR-based platform as shown in Fig. 4.

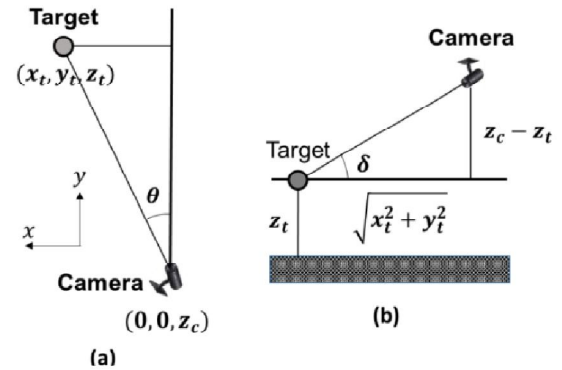


Fig.3:Schematic view representing (a) the pan and (b)the tilt angles between the Vicon camera and the target

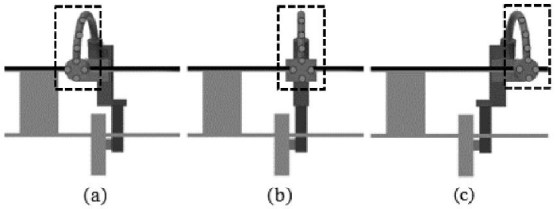


Fig. 4. 3D configuration of the VR-based platform withmarkers at three different positions in wig-wag movements aligned in: (a) 12. 5° to the right, (b) in the center and (c) 12. 5° to the left from the centerline

B. C-Arm Prototype

The C-Arm prototype, also referred to as the C-Arm Mini, is a downscaled replica of the current operating C-Arms as seen in Fig. 5. Just like the original C-Arm that it is replicating, the C-Arm Mini has five main components. These include the base, vertical slider, horizontal slider, vertical rotator, horizontal rotator, and the C-Orbital. First, a firm foundation for the base of the C-Arm was constructed using a galvanized steel frame wherein the circuit board and a 12V battery are fastened. The circuit board consists of a standard Arduino Uno coupled with five motor units, each responsible for signaling the C-Arm's five degrees of freedom. Two of the motors power the vertical and horizontal linear actuators responsible for translational movement. Two more motors activate the rotation of the C-Arm about the vertical and horizontal axes, and the remaining motor drives the orbital motion of the C-Orbital. All motors are programmed by and controlled with MATLAB/Simulink Arduino module.

C. C-Arm Virtual Model

The physical prototype, the C-Arm Mini, is simulated virtually in the MATLAB Simscape module as shown in Fig. 6. The virtual prototype allows for faster modifications and feasibilitychecks. In addition, the forwards and inverse kinematics of the virtual C-Arm are much easier derived. Because of this, the kinematics and the data acquisition become much easier through virtual prototype using Simulink. For further validation and evaluation, the virtual robot is linked to the physical C-Arm Mini, and the movement of both robots are synchronized. This allows for comparison and contrast of the dynamics, mechanics, and programing.

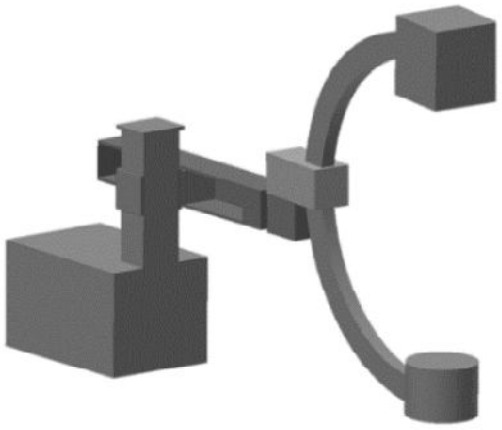


Fig. 6: Isometric view of virtual C-Arm assembly

To develop the virtual model, Autodesk Inventor was used to create the five components of the C-Arm using CAD renderings. The five components were designed as a scaled-down and simplified version of the original C-Arm. Once each component was rendered, an assembly of the C-Arm virtual robot was made using Autodesk Inventor again. This assembly was then exported as an extensible markup language (XML) file for the use of the multi-dynamics toolbox for MATLAB Simulink. The automatics assembly transformation from Inventor to Simscape multibody required the download of the Simscape plug-in for Inventor.

D.MATLAB/Simulink Model

Once in MATLAB, the complete assembly of the virtual robot is represented as blocks. These blocks include the five components of the robot and each individual joint of the robot. With the joint blocks, data acquisition and signal processing can be done directly in Simulink. For a simple case, a PID controller is applied to the vertical translational joint to allow, for example, vertical position change of the C-Arm, as shown in Fig. 7. The physical component blocks and joint blocks are a part of a simple Graphical User Interface (GUI). This GUI will allow the user to actuate the Vertical Joint via the provided slider in Fig. 7.

As an example, the joint is asked to move from a 4.25-inch vertical height, which is in the middle range, to a 1.1-inch vertical height, which is close to the lowest extreme position. The desired position change is selected by operator using the GUI by simply dragging the slider from a value of 4.25 to a value of 1.1. The position data of the translating joint and the actuation torque required by the physical motor of the C-Arm Mini can be derived automatically and presented in the MATLAB/Simulink.

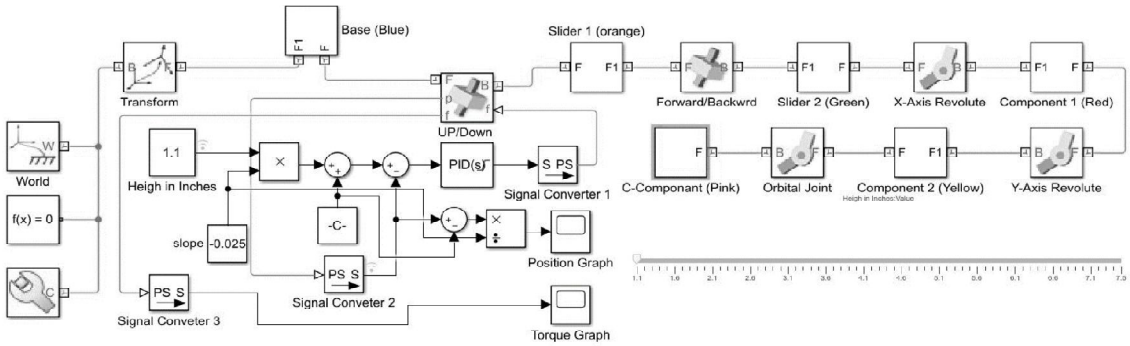


Fig.7: A Simulink visual model showing the application of (PID) controller to the vertical slider of the virtual C-Arm

IV. RESULTS AND DISCUSSION

A. MATLAB/Simulink Simulation Results

To choose the best control method for the C-Arm Mini, three different controllers were created and applied to the virtual C-Arm for evaluation and comparison. The three controllers include (P) controller, (PI) controller and (PID) controller. The position signal and the torque input signal of all three controllers were consider in choosing the best option.

The results of the (P) controller were promising in the fact that the position settling time was well below 5 seconds. However, no matter the P value, the system oscillated too much for the application of the C-Arm as seen in Fig. 8. The torque values of the (P) controller also showed large negative values which are preferably avoided as shown in Fig. 9. This meant that the (P) controller was not suitable for this application.

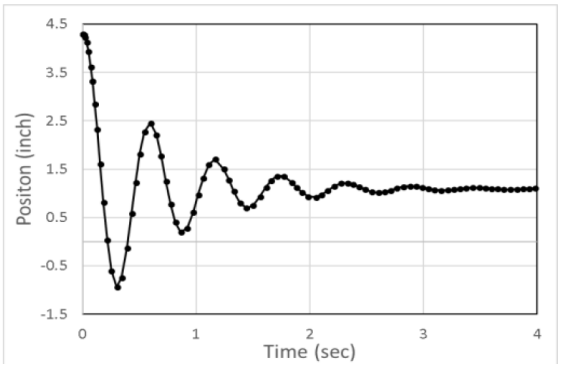


Fig.8: Position vs Time graph of vertical slider of the C-Arm Mini using (P)Controller

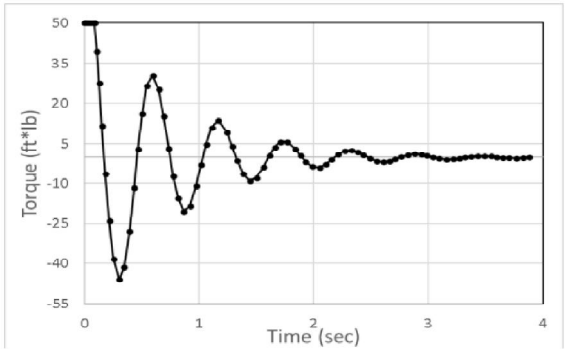


Fig.9: Actuator Torque Graph of the Vertical Slider of the C-Arm Mini using (P) controller

In order to acquire better results, a (PI) controller was applied next. The (PI) controller much like the (P) controller showed a much lower settling time than five seconds. However, the large overshoot and oscillation were not feasible for the application of the C-Arm as seen in Fig. 10. In addition, the (PI) controller also relies on large negative torque values to settle itself as shown in Fig. 11. This is preferably avoided.

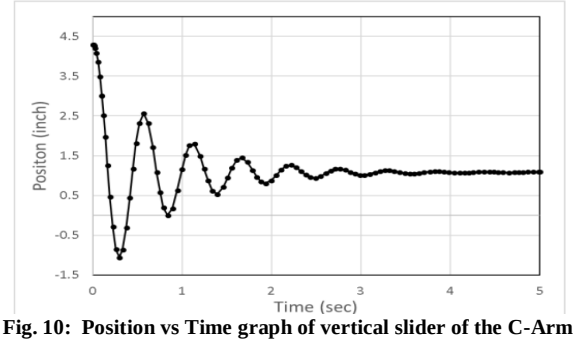


Fig. 10: Position vs Time graph of vertical slider of the C-Arm Mini using (PI) controller

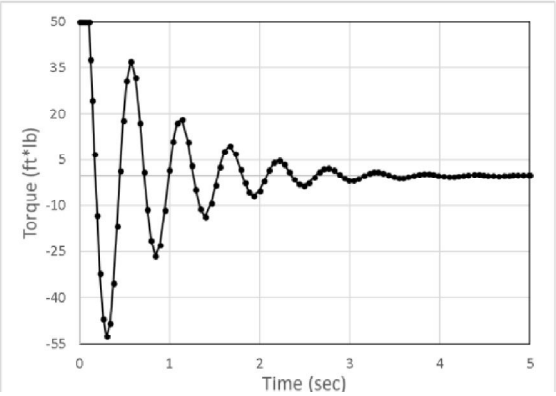


Fig. 11: Actuator torque graph of the vertical slider of the C-Arm Mini using (PI) controller

The application of the (PID) showed the best results for positioning, as shown in Fig. 12. The vertical position never reached negative values unlike the (P) and (PI) controller. The overshoot was within an acceptable range of 1.4%. In addition, the position settling time of the (PID) controller, with a value of two seconds, was well below the required five second limit, and significantly lower than the (P) and (PI) controller.

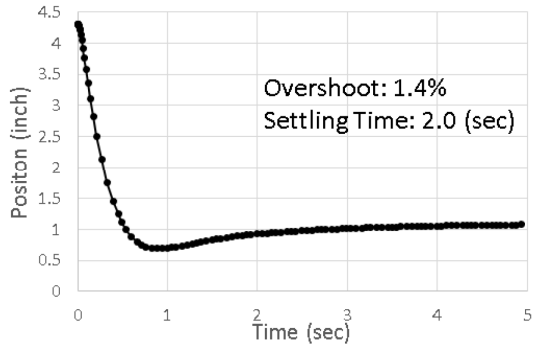


Fig.12: Position vs Time graph of vertical slider of the C-Arm Mini using (PID) controller

The actuator torque values of the (PID) controller never reached significantly negative values, which is preferred. The larges negative value reached was about -1.0 $ft \cdot lb$, which is acceptable and practical for the use of maneuvering the C-Arm Mini prototype. The torque can be seen in Fig. 13.

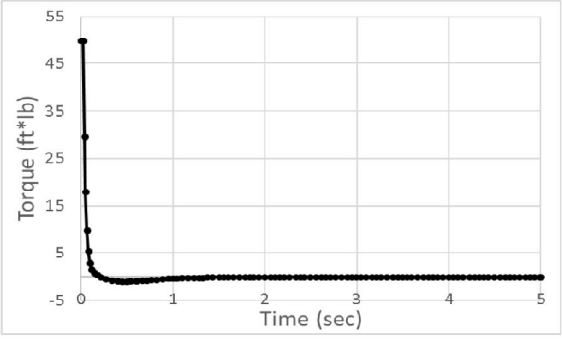


Fig.13: Actuator torque graph of the vertical slider of the C-Arm Mini using (PID) controller

B. Discussion and Future Work

From the results, it can be concluded that the best control option for moving the C-Arm Mini is in fact the (PID) controller. This decision is based on the fast position settling time of two seconds, and the low negative values of actuator torque required by the (PID) controller. In addition to the fast settling time of the (PID) controller, the oscillation of position was significantly less than the (P) and (PI) controllers.

The current C-Arm Mini is able to maneuver itself to designated positions based on user inputs through a GUI. However, the next future step is to sync the C-Arm Mini with a 3D motion capture system. By placing markers on critical locations of the C-Arm Mini and placing motion capture cameras around the prototype, the C-Arm Mini will be able to recognize its position in space and thereby maneuver itself into required positions. This will be accomplished through the use of Vicon motion capture technology.

In addition to the motion capture, the virtual environment of the C-Arm will be completed,as illustrated in Fig. 14,and synced to the C-Arm Mini, meaning that operators can observe the movement of the robot and the virtual version in real time. The virtual environment will also aid in training users to operate the C-Arm with the integrated Vicon motion capture technology.

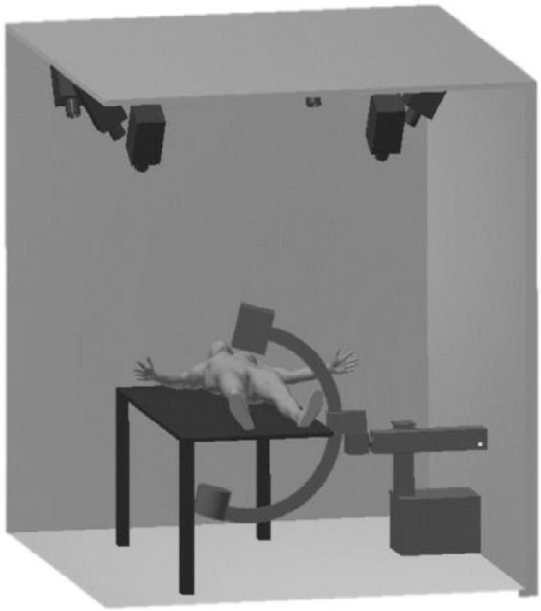


Fig. 14: Virtual environment for C-Arm scanning

For the object recognition, the desired target (reference) marker's images will be first created by VR-based platforms (or actual measurements) similar toFig.15 [7]. The images are then compared and adjusted by the reference image using the object recognition techniques. The object recognition technique includes appearance-based, contour-based, and model-based methods [8]. Some techniques used in automatic target acquisition will be adapted to

enhance object classification and recognition during the repositioning process of the C-arm[9].

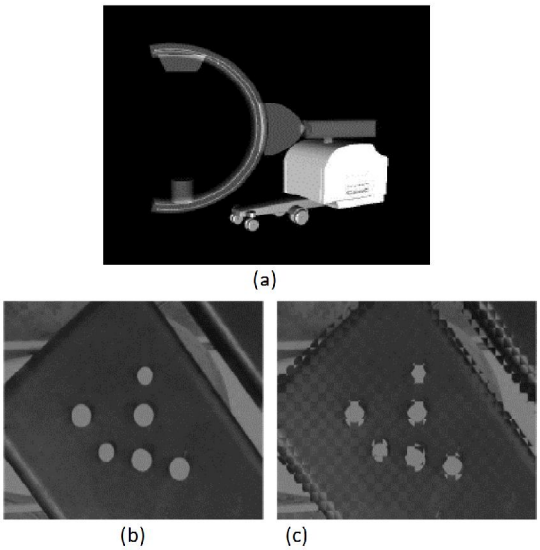


Fig. 15: Visualization for the C-Arm visual surveying task using the VR-based platform - 3D virtual models of (a) C-Arm complete assembly; (b) markers at target position; (c) close to target position

CLOSING REMARKS

To obtain the best control method for the C-Arm Mini prototype, three different controllers were implement to the vital C-Arm using MATLAB/Simulink. The three controllers were the (P), the (PI) and the (PID) controllers. In order to evaluate the feasibility of these controllers, a close look was taken at the position graphs and the actuator torque graphs. By comparing the different graphs, the (PID) controller was chosen to be the most feasible for the C-Arm Mini application. This decision came to be because of the low settling time of the (PID) controller position values, fast settling time of the position graph, and the low negative values of the actuation torque.

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