Interactive Guidance System for C-Arm Repositioning without Radiation

Visual Servoing for Camera Augmented Mobile C-arm (CAMC)

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Abstract. The problem of repositioning mobile C-arms to defined target locations during surgical procedures currently requires not only time, but also skill and additional radiation exposure. This paper shows a guidance system based on the previously introduced camera augmented mobile C-arm (CAMC). Techniques of visual servoing are applied in order to present the repositioning task in the parameter space of the C-arm. Here we describe a representation for the estimated parameters in order to provide an easy to use interface that helps to speed up relocation procedure in the surgery room. The system which is based on an interactive 3D model, is controlled by tracking visible markers on the patient's skin using an optical camera attached to the X-ray housing. The visual servoing methods are used to guide the C-arm to target positions by the representation of the interactive visual guidance system. Addititionally, the system provides a number of tools for feedback to assess the required accuracy of the repositioning task. First tests for C-arm repositioning were performed in a laboratory environment.

1 Introduction

The mobile C-arm has become an essential tool in everyday trauma and orthopedic surgery. During the course of surgical interventions, the mobile C-arm frequently has to be moved by OR-staff. This results in the problem of finding the exact position again in order to compare the second image/sequence with the one acquired before the C-arm was (re)moved. In order to guarantee accurate and fast repositioning of the C-arm, a simple step-by-step approach is required. In addition, a system interacting with the OR-staff should be especially unambiguous and self-explaining as possible to avoid error and the need of training.

The camera augmented mobile C-arm (CAMC) [1, 2] has an attached optical camera mounted beside the X-ray housing which in combination with a navigation software allows to minimize the exposure to radiation. By using a double mirror system, X-ray images can be aligned and overlaid on real-time images for simultaneous display. This merely requires an one-time calibration step supposed the patient does not move. If the patient moves simply a new x-ray image has to be aquired and the modalities are aligned again. Additionally, CAMC supports repositioning tasks by using optical image-based visual servoing. This is achieved by tracking fiducals and comparing their locations to given target positions. Using this information visual servoing techniques, as described in [3], iteratively compute joint increments. Due to the manual manipulation nature of the mobile C-arm unit, this information is passed to the OR-staff, which adjusts the joints accordingly.

The previous introduced system [3] only provides the parameters in C-arm coordinates. However, the main contribution of the system described in this paper is to provide an easy to use interface. Thus the visual servoing procedure is extended by a user interface in order to make the repositioning task simple and unambiguous for the surgical staff in the OR. This contains the display of the isolated C-arm parameters as instructions on a 3D model of the C-arm and for the confirmation of the correct repositioning a visualization of a difference video image.

2 C-arm control and motion model

Visual servoing aims to control the C-arm using the visual information taken from the on-board camera observing the scene at the current position $\mathcal{F}$ such that it reaches the desired (or the reference) position $\mathcal{F}^*$. If we denote by $\mathbf{q}$ the vector containing the current positions of the joints, the objective of visual servoing is then to compute the direction and the amplitude of the increments of the joints, that correspond to $\dot{\mathbf{q}}$, in order to accomplish the positioning task. Consequently, we need to model the forward kinematics and the Jacobian of the C-arm.

The kinematic of the C-arm has five degrees of freedom : height, wigwag-movement, length, angular and orbital movement. We assigned a coordinate frame to each joint according to the Denavit-Hartenberg rules. Let ${}^{i}\mathbf{A}_{i+1}$ be the (4×4) transformation matrix from the coordinate system of the joint $i+1$ to the coordinate system of the joint i. Multiplying the different transformation matrices makes it possible to obtain the camera pose wrt. the world reference frame: ${}^{0}\mathbf{A}_{6} = {}^{0}\mathbf{A}_{1}{}^{1}\mathbf{A}_{2}{}^{2}\mathbf{A}_{3}{}^{3}\mathbf{A}_{4}{}^{4}\mathbf{A}_{5}{}^{5}\mathbf{A}_{6}$ The transformation matrix ${}^{5}\mathbf{A}_{6}$ takes into account the rotation between the coordinate system of the last joint and the coordinate system of the camera.
To relate the motion of the camera to the motion of the C-arm joints, we have to compute the manipulator Jacobian $\mathbf{J}_{carm}$ of the C-arm. It converts the velocities of the single joints $\dot{\mathbf{q}}$ to the Cartesian velocity of the camera $\mathbf{v}_c$.
The C-arm consists of five joints so $\mathbf{J}_{carm} \in \mathbb{R}^{6\times 5}$. Its entries can be derived from the forward kinematics. The rotation axis $\mathbf{z}_i$ of each joint is found in the 3rd column of the matrix ${}^{0}\mathbf{A}_{i} = {}^{0}\mathbf{A}_{1} \dots {}^{i-1}\mathbf{A}_{i}$, where the origin $\mathbf{o}_i$ is found in the 4th column.. Equation 1 lists first the column of the manipulator Jacobian for a

prismatic joint (like length and height of the C-arm) and second for a revolute joint (like wigwag, angular and orbital movement).

$$\mathbf{j}_i = \begin{pmatrix} \mathbf{z}_{\boldsymbol{i}} \\ \mathbf{0} \end{pmatrix} \; ; \mathbf{j}_i = \begin{pmatrix} \mathbf{z}_{\boldsymbol{i}} \times (\mathbf{o}_5 - \mathbf{o}_i) \\ \mathbf{z}_{\boldsymbol{i}} \end{pmatrix} \tag{1}$$

2.1 Visual Servoing

At the desired position $\mathcal{F}^*$, a 3D point $\boldsymbol{\mathcal{X}}$ is projected on a virtual plane perpendicular to the optical axis of the camera into a 2D point $\mathbf{m}^*$:

$$\mathbf{m}^* = (x^*, y^*, 1) \propto \begin{bmatrix} \mathbf{I}_{3\times 3} \; \mathbf{0}_{3\times 1} \end{bmatrix} \boldsymbol{\mathcal{X}} \tag{2}$$

The same 3D point $\boldsymbol{\mathcal{X}}$ is projected into a 2D point $\mathbf{m}$ in the current camera position $\mathcal{F}$: $\mathbf{m} = (x, y, 1) \propto \begin{bmatrix} \mathbf{R} \; \mathbf{t} \end{bmatrix} \boldsymbol{\mathcal{X}}$ where $\mathbf{R}$ is the rotation matrix and $\mathbf{t}$ is the translation vector between the two coordinate systems $\mathcal{F}$ and $\mathcal{F}^*$. The information given by a pinhole camera, which performs a perspective projection of 3D points, is an image point $\mathbf{p} = (u, v, 1)$ verifying $\mathbf{p} = \mathbf{K}\mathbf{m}$ where $\mathbf{K}$ is the camera internal parameter matrix.

Visual servoing using 2D target image can be accomplished by building a vector $\mathbf{s}$, containing visual information extracted from the current acquired image (at the current position $\mathcal{F}$), converging to a vector $\mathbf{s}^*$ containing visual information extracted from the reference image (at the reference position $\mathcal{F}^*$). In our case, the visual information are the image coordinates of the n markers:

$$\mathbf{s} = \begin{bmatrix} \mathbf{m}_1^\top \; \mathbf{m}_2^\top \; \ldots \; \mathbf{m}_n^\top \end{bmatrix}^\top \tag{3}$$

An interaction matrix (also known as image jacobian) $\mathbf{L}$ is then defined in order to establish the relationship between the Cartesian velocity of the camera $\mathbf{v}_c$ and the derivative of the vector $\mathbf{s}$ wrt. time. This relationship can be written as: $\dot{\mathbf{s}} = \mathbf{L}\mathbf{v}_c$. The $(3n \times 6)$ interaction matrix $\mathbf{L}$ can be expressed with the following formula: $\mathbf{L} = \begin{bmatrix} \mathbf{L}_1^\top \; \mathbf{L}_2^\top \; \ldots \; \mathbf{L}_n^\top \end{bmatrix}^\top$ where:

$$\mathbf{L}_i = \begin{bmatrix} \frac{1}{Z_i} & 0 & -\frac{x_i}{Z_i} & x_i y_i & -(1 + x_i^2) & y_i \\ 0 & \frac{1}{Z_i} & -\frac{y_i}{Z_i} & (1 + y_i^2) & -x_i y_i & -x_i \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Finally the vector $\mathbf{s}$ is servoed using the task function approach [4, 5] by minimizing iteratively the following vector $\mathbf{e} = \widehat{\mathbf{L}}^+(\mathbf{s} - \mathbf{s}^*)$, where $\widehat{\mathbf{L}}^+$ is an approximation of the pseudo-inverse of the true interaction matrix $\mathbf{L}^+ = (\mathbf{L}^\top \mathbf{L})^{-1} \mathbf{L}^\top$. If we differentiate this equation, we obtain:

$$\dot{\mathbf{e}} = \frac{d\widehat{\mathbf{L}}^+}{dt}(\mathbf{s} - \mathbf{s}^*) + \widehat{\mathbf{L}}^+ \dot{\mathbf{s}} = (\mathbf{O}(\mathbf{s} - \mathbf{s}^*) + \widehat{\mathbf{L}}^+ \mathbf{L})\mathbf{v}_c \tag{4}$$

where $\mathbf{O}(\mathbf{s} - \mathbf{s}^*)$ is a (6×6) matrix that can be neglected for $\mathbf{s} \approx \mathbf{s}^*$. Let's consider the control law: $\mathbf{v}_c = -\lambda \mathbf{e}$ where λ is a positive scalar. Plugging this equation into equation (4), we obtain the following closed-loop equation: $\dot{\mathbf{e}} = -\lambda(\mathbf{O}(\mathbf{s}-\mathbf{s}^*) + \widehat{\mathbf{L}}^+\mathbf{L})\mathbf{e}$. It is well known from the control theory that this non-linear system is locally asymptotically stable in a neighborhood of $\mathbf{s} = \mathbf{s}^*$, if and only if, the matrix $\widehat{\mathbf{L}}^+\mathbf{L}$ has eigenvalues with a positive real part $real(eig(\widehat{\mathbf{L}}^+\mathbf{L})) > 0$. Obviously, if the pseudo-inverse of the interaction matrix is well approximated, we have: $\widehat{\mathbf{L}}^+\mathbf{L} \approx \mathbf{I}$ and the control law is locally asymptotically stable. Then, using the camera Cartesian velocity $\mathbf{v}_c$, it is possible to compute the joints increments $\dot{\mathbf{q}}$ given the pseudo-inverse of the C-arm Jacobian:

$$\dot{\mathbf{q}} = \mathbf{J}^+_{carm}\mathbf{v}_c \tag{5}$$

3 Reposition guidance

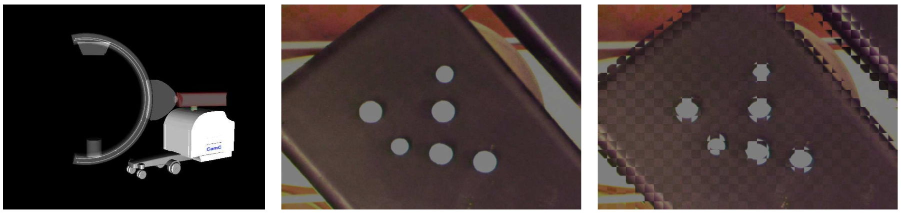
During the reposition task, the joints of the C-arm have to be moved in a structured way by the OR-stuff to re-assume the correct target position. In order to achieve this goal an easy to use and unambiguous guidance system is presented to the staff in oder to fulfill the required motion $\dot{\mathbf{q}}$ estimated by the visual servoing algorithm. Given the numbers of the parameters in C-arm coordinate system are difficult to understand, misinterpretation can easily prolong the process of repositioning.

To cope with the problem of information representation several interfaces were created and tested. The main component of the guidance system is an interactive 3D model of the C-arm. The joints of the model can be moved independently featuring the same five degrees of freedom as the real mobile C-arm. Figure 1a shows a screenshot of the 3D model. Within the model the suggested movement estimated by the visual servoing algorithm is simulated to the OR-staff.

During the process of motion animation, the affected joint was displayed in its corresponding color while the inactive parts remained gray. However, to give a better impression of the motion, passively moved parts remained uncolored, but were displayed translucent just like the active joint. For simplicity of the user interface and interaction only one joint at a time was assumed to be moved and simulated accordingly. Considering the fact that the 3D model is impractical for conveying quantitative information, e.g. express the magnitude of motion, supplemantary indicators were added. For this purpose, a gauge in terms of a progress bar was used to display relative motion extent. Additionally, the proximity of the markers to the target position by means of the euclidean norm was color-coded to give an easy and fast visual impression of the progress made during the visual servoing steps.

For qualitative validation of the repositioning task checkerboard views, commonly used for registration verification purposes, for both the video and the x-ray were integrated into the guidance system. Therefore, the images of the video camera and x-ray at the target position are stored. The checkerboard difference image shows from the beginning of the visual servoing procedure, the current video overlayed with the stored reference image (Fig. 1).

Fig. 1. Visualization for the CAMC visual servoing task



(a) 3D model of C-arm (b) At target position (c) Close to target position

4 Results and conclusion

Tests for the visual servoing were performed on cadaver and published [3]. First tests on the usability of the representation for the visual servoing parameters were conducted on phantoms and showed the validity of the designed system. Even untrained persons could manipulate the C-arm to the indicated target position and orientation. Tests in real scenarios are subject for further work within this project.

The CAMC system and its extension for repositioning the C-arm by means of visual servoing can facilitate various applications in the domain of trauma and orthopedics surgery where the use of mobile C-arms is essential. Exemplary applications that can benefit from the proposed system are e.g. pedicle screw placement, im-nail locking, or other implant positioning procedures. An intuitive user interface and representation of available data is a crucial step towards the acceptance of this system in the OR.

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