Automatic guidance of a surgical instrument with US based visual servoing (Abstract)

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I. Objectives

Ultrasound (US) probes are external sensors capturing real-time information of the inner structure of an organ. They are often used if it is impossible to insert an endoscope into the organ to provide an internal view. The US image gives only a 2D cross-section of the 3D working volume which contains no depth information. This imposes high demands on the surgeon's hand/eye coordination capabilities. Therefore, manual US guided interventions are mainly limited to simple tasks such as puncture of lesions.

To overcome this difficulty, a possible solution consists in automatically realizing the hand/eye synchronization. The proposed approach consists of an image guided robotic system using US-based visual servoing: in the image plane the instrument is detected and a desired position is specified by the surgeon. The position error is then used to move the instrument towards the specified goal. This guarantees that the surgical instrument is always visible in the image plane.

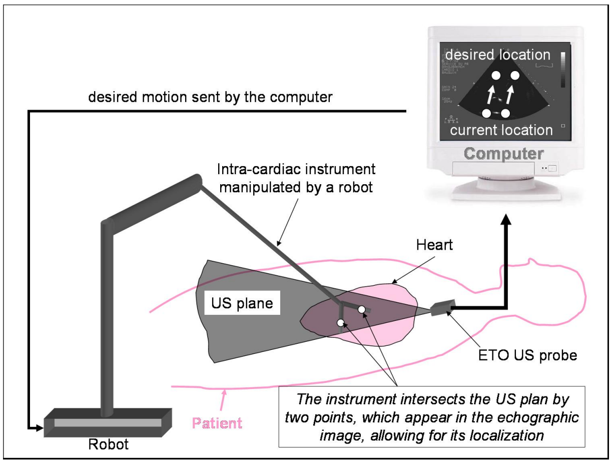

Fig. 1 System description

II. Methods

The main methodoligical development in this research concerns the design of a visual servoing loop. Visual servoing requires the knowledge of the spatial relation between the displacement of the surgical tool and its corresponding displacement in the image. Therefore, the US image jacobian needs to be calculated, *i.e.* the geometrical and kinematic models have to be derived. Thereafter, the obtained image jacobian is used in a classical visual servoing loop.

In order to develop the geometrical and kinematic models, some assumptions were made:

- The geometrical and kinematic models of the robot are considered to be well-known.
- The US image is assumed to be a representation of a 2D cross-section of the 3D workspace (refered as *echographic plane* or *echographic image*).
- The intersection of the surgical tool (pair of forceps) with the echographic plane is represented by two points in the image.
- The US probe pose (i.e. position and orientation) with respect to the robot base is assumed to be known.

Under these assumptions, the image jacobian can be calculated and used to close the visual servoing loop.

A. Modelling

The first step is to calculate the geometrical model of the system. This model provides the vector $\mathbf{s}$ of the instrument coordinates in the image as a function of the instrument pose $\mathbf{p}$. The obtained model can be written as:

$$\mathbf{s} \;=\; \mathbf{A}(\mathbf{p})\,\mathbf{p}\;. \tag{1}$$

Then, assuming that the instrument is a rigid body, the kinematic model can be computed by derivation of equation (1):

$$\dot{\mathbf{s}} \;=\; \mathbf{J}\,\dot{\mathbf{p}}\;, \tag{2}$$

with $\mathbf{J}$ denoting the image jacobian.
In visual servoing, the inverse image jacobian $\mathbf{J}^{-1}$ needs to be calculated which can be done analytically in the case considered here.

B. Control

The image jacobian $\mathbf{J}$ depends on the geometrical model of the robot and the relative pose of the US probe with respect to the robot base frame which are not perfectly known. Therefore, the inverse image jacobian $\mathbf{J}^{-1}$ has to be replaced with its estimated value $\widehat{\mathbf{J}^{-1}}$.
A linearizing proportional control law with gain k is used to calculate the desired instrument velocity:

$$\dot{\mathbf{p}} \;=\; k\,\widehat{\mathbf{J}^{-1}}\,\mathbf{e} \;=\; k\,\widehat{\mathbf{J}^{-1}}\,(\mathbf{s}_{\,d} - \mathbf{s})\;\;, \tag{3}$$

$\mathbf{s}_{\,d}$ being the desired position in the image plane.
Numerical simulations were performed to evaluate the robustness of the control loop with respect to parameter uncertainties in the model (*eg.* geometrical parameters of the robot). The major parameter uncertainties lie in the estimation of the relative pose between US probe and robot base. Simulations indicate that within an error of 10° in orientation, or within 10mm in translation, the control law is still stable.

III. Results

In vitro experiments have been performed to validate the approach. The experimental set-up consists of a box full of water in which an US probe is placed and a surgical tool moved by a robot. The used robot (MC2E, french acronym for compact manipulator for endoscopic surgery, developed at the Laboratoire de Robotique de Paris) is especially suited for minimally invasive robotic surgery applications and provides, with its spherical structure, 4 degrees of freedom at the instrument tip.
To follow the instrument echoes in the echographic image, real time detection, labelling, and tracking algorithms were developed. These algorithms robustly compute the coordinate vector $\mathbf{s}$ which is then transmitted via a TCP/IP connection to the robot controller. The overall computation time is less than 35 ms, thus being bellow the 40 ms frame rate of the US probe. The experiment itself is performed as follows:
A user selects the desired goal $\mathbf{s}_{\,d}$ in the echographic image. Then the current instrument coordinate $\mathbf{s}$ in the image and the corresponding error $\mathbf{e}$ are calculted. The desired velocity of the instrument is computed by multiplying the estimated inverse image jacobian $\widehat{\mathbf{J}^{-1}}$ with the error $\mathbf{e}$. The result is then sent to the robot controller.
First experiments are promising with respect to robustness of the vision algorithms and overall system stability.

IV. Conclusion

To overcome the difficulties in hand/eye coordination during manual US-guided interventions the proposed approach is feasible. The chosen control law is sufficiently robust with respect to parameter uncertainties. The developed vision algorithms are able to reliably track the instrument in the speckled ultrasound images. First in vitro experiments realizing the visual servoing control loop were successful.