Paper Review

Title: Vision-Assisted Control for Manipulation Using Virtual Fixtures

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Summary:

This work focuses on the implementation of a vision-based motion guidance method, called virtual fixtures, on admittance-controlled human-machine cooperative robots with compliance. The robot compliance here refers to the structural elastic deformation of the device. The system uses computer vision as a sensor for providing a reference trajectory, and the virtual fixture control algorithm then provides haptic feedback to implemented direct, shared manipulation. It then discusses experiments to evaluate both speed and accuracy of the proposed constraints on human speed and accuracy versus free motion in a steady-hand paradigm. The result indicates improvements in the performance of human in the desired task execution.

Paper Selection and relevance:

One of the main objectives of our project, Robotically Assisted Cochlear Imaging and Access, is implementation of virtual fixtures for precise navigation of the implant electrode inside the cochlea. Since we are also working in the steady hand paradigm I found this study highly relevant to our objective. Also considering my familiarity with the senior authors of this paper and the courses that I took with both of them I believe they have a considerable expertise in this area and this was also another major reason for selection of this paper.

Overview of the Method and Results:

In the Steady-Hand paradigm, the relationship between velocity and motion is derived by considering a virtual contact between the robot tool tip and the environment. In most cases, this contact is modeled by a linear viscous friction law:

$$V = \frac{1}{K} F$$

Here we call the coefficient 1/k, C or admittance. When using the above equation the robot stiffness in all direction is equal. A virtual fixture generalizes this model to include anisotropic admittances. If delta represents the instantaneous “preferred” directions of motion for the tool tip then the projection matrix is defined as D:

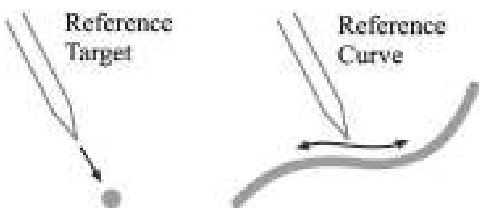
$$D_\delta \equiv \delta(\delta'\delta)^{-1}\delta'.$$

Now if we decompose the input force into two components, one in direction of preferred motion and another perpendicular to it, we can rewrite the control law as follows, where a new admittance is introduced with reduces the component of the force input in the nonpreferred direction

$$\begin{aligned}\mathbf{v} &= c(\mathbf{f}_{\boldsymbol{\delta}} + c_\tau \mathbf{f}_\tau) \\ &= c(D_{\boldsymbol{\delta}} + c_\tau(I - D_{\boldsymbol{\delta}}))\mathbf{f} = G(c, c_\tau, \boldsymbol{\delta})\mathbf{f}.\end{aligned}$$

Therefore, the final control law is in the general form of an admittance control with a time-varying matrix G. If we choose $c_\tau = 0$ then it would create hard virtual fixture making it impossible to move in any direction other than the preferred direction. Other cases can be named soft virtual fixtures.

With this concept two type of constrains can be identified as represented in the following figure, in the Reference Target mode, the robot directs the tool toward a specific point while in the reference curve mode the robot constrains the user motion along a 3-D Cartesian path.



The information from computer vision is used to identify the reference geometries; however the paper assumes that those references are known.

This function represents the transfer function relating the robot velocity to the human input force.

$$\frac{V_i(s)}{F_i(s)} = \frac{s + (k_p + k_v s)c}{m_i s^2 + (b_i + k_v)s + k_p}$$

The paper then describes extension of this technique to higher dimensional subspaces of the robots configuration space such as situations where the desired task demands constrains that are inherently volumetric. It also introduces the velocity scaling as the final step of implementation to account for fine positioning and large, coarse motion.

Next, they performed experiments with the robot operating autonomously to generate the baseline data then they measured the performance and accuracy from multiple users to evaluate their method on the steady hand robot.

The results indicated that hard virtual fixtures provided the best performance. 78% improvement in accuracy and 32% in execution time was reported compared to a nonconstrained motion.

Analysis and Review:

This work introduces a specific instance of virtual fixtues which does not involve the robot kinematics. It assumes that the kinematics is handled elsewhere and therefore only computes the required Cartesian velocities. Of course another processing block can be added at the end of this which can compute the velocities for the robot which is typically required in terms of joint velocities, which was done for some of the steady hand papers. The limitation of this work is when the robot cannot fulfill the required Cartesian velocities. However as it is mentioned, a solution for this is to use the current Cartesian position of the robot in combination with external sensor (camera) to compute required Cartesian velocity in a closed loop fashion. The details for the later are not discussed in this paper.

On the other hand, a generalization and combination of both these into one processing block can be done similar to the work done in [1, 2]. In the implementation of this method, in derivation of the joint velocities from Cartesian velocities should be handled very carefully where the configuration is of the robot joints are coupled. It should also be mentioned that the Jacobian of a manipulator is only a first order approximation and therefore finding an iterative solution to the kinematics equations works only for the most non-trivial robot.

Overall, this paper is very well written and clearly shows the expertise and familiarity of the authors with the subject. This is a strong team. They have been persistently working on this filed and been generating solid work on relevant issues. However for the implementation purposes and when compared to other methods, it may be hard to generalize this method to other robots [1,2]. The number of subjects may not be adequate to make the results statistically significant and rely on it as a performance indicator for a general use. It would be more appropriate to consider this as a small study for proof of a concept and then conduct larger experiments for more convincing evidence of performance improvement.

References:

[1] A. Kapoor, M. Li, and R. H. Taylor, “Constrained control for surgical assistant robots,” in IEEE International Conference on Robotics and Automation, 2006,pp. 231_236.

[2] M. Li, A. Kapoor, and R. H. Taylor, “A constrained optimization approach to virtual fixtures, in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005, pp. 1408-1413.

[3] P. Marayong and A. M. Okamura, "Speed-Accuracy Characteristics of Human-Machine Cooperative Manipulation Using Virtual Fixtures with Variable Admittance," Human Factors, Vol. 46, No. 3, pp. 518-532, 2004.