Abstract—To perform semi-automated surgical tasks or to assign virtual fixtures for telemanipulated surgical procedures, accurate correspondence between preoperative and intraoperative organ geometry is required. To overcome organ deformation and shift relative to pre-operative images, this paper proposes using force-controlled exploration to update organ geometry using a deformable registration of a pre-operative model to the surgical scene. Since continuum robots can offer deep access into the anatomy, we explore the unique challenges associated with their use to achieve force-controlled exploration. A mixed feedback control law is proposed whereby joint-level and end-effector position measurements are used to satisfy a reference motion trajectory. A hybrid force/position controller is presented using sensory input from magnetic tracking and force sensing. Validation of the proposed control algorithms is achieved on the IREP (a single port access surgical system). Experimental results show that, despite deformation of an organ, the surgical plan can be deformably registered using force-controlled exploration data via an implementation of coherent point drift registration. Future work includes integrating intrinsic force sensing, updating virtual fixture laws in the presence of organ deformations or swelling, and semi-automation of surgical tasks.

I. INTRODUCTION

During robot-assisted minimally invasive surgery, accurate registration between the pre-operative model containing the surgical plan and the intraoperative surgical scene enables key capabilities such as virtual fixtures for assistive telemanipulation and semi-autonomous execution of surgical tasks. However, between planning/imaging and surgery, organs shift and deform due to gravitational loads and changing boundary conditions with neighboring organs due to surgical dissection. This paper explores the feasibility of using continuum robots for autonomous scanning and registration of organ geometry to pre-operative information. Continuum robots are chosen for this task as a representative example among minimally invasive robotic devices that allow deep reach into the anatomy (e.g. catheters and wire-actuated snake-like robots).

The need to reconcile pre-operative data to the intraoperative surgical field has motivated many years of research on deformable registration. A summary and classification of deformable registration techniques is available in [1]. The majority of deformable registration works focus on using intraoperative imaging or computer-vision/laser scanning (e.g. [2]) to achieve the data needed to update the organ registration and surgical plan. Force-controlled exploration/palpation offers new capabilities for registration: palpation enables simultaneous use of geometry and stiffness for registration, in addition, palpation with continuum robots can reach anatomy out of the field of view of other imaging/vision tools and investigate areas obscured by blood or other fluids. Future force-controlled exploration should be used to augment information from 3D vision or laser scanning. To prove feasibility of this method, we limit the scope of this work to exploring and overcoming challenges in geometry-based registration based on force controlled exploration using continuum robots.

The use of force-controlled exploration of organ shape was proposed in [3], where effects of scan patterns on the accuracy of shape estimation were explored. Recently, in [4] the use of force-controlled exploration for achieving deformable registration and updating the geometry of a virtual fixture was presented with implementation on a rigid Cartesian stage robot and using the daVinci research kit (dVRK). Our work in this paper extends these efforts by expanding the robot architectures where feasibility of this approach has been tested. While the Cartesian robot has very high accuracy and no deflections and the dVRK slave has good accuracy [5] (within 1.5 mm) and small deflections, a typical continuum robot will have poor accuracy and significant deflections, thus motivating new approaches in robot control to overcome these challenges.

The accurate registration of a preoperative surgical plan allows for updating virtual fixtures and (semi) autonomous execution of surgical tasks: examples where these capabilities are useful include force- and velocity-controlled ablation along a path and (semi) autonomous suturing. In addition to accurate registration, an accurate kinematic model is required for semi-automated task execution in the absence of end effector sensing. This is difficult for continuum robots which often have poor accuracy. Telemanipulation can overcome these issues via user supervision with sub-millimetric accuracies attainable [6], but that is separate from the use of accurate virtual fixtures or task automation. We will follow the mixed-feedback approach in [7] by sensing the end effector position and closing the loop with a magnetic tracker at the robot tip.

In this paper, we present a control framework to achieve blind force-controlled exploration and registration with a update of the hybrid-force position law found in [8]. We extend...
[4] by implementing the exploration and registration using a continuum robot, which motivates a significant change in the framework for motion and force control to allow success of force-controlled organ exploration.

II. Control Framework

The Insertable Robotic Effectors Platform (IREP) is a two-armed multi-backbone continuum robot designed for single port or natural orifice surgery. Each arm includes two continuum segments, a planar five-bar parallelogram linkage, an insertion stage, and a wrist. For this paper, we use only the right arm, equipped with a spherical palpation probe end-effector for environment exploration and location feedback from a magnetic tracking marker. Full design and modeling details for the kinematics of this robot are available in [9], [10]. The overall control framework in the subsequent sections appears in Fig. 1.

A. Continuum Robot Kinematic Model

The robot kinematics use the framework describing constant curvature continuum manipulators introduced in [11]. Salient aspects of this framework will be summarized here for readability. Each continuum segment achieves bending by pushing and pulling on super-elastic nitinol backbones. Segment kinematics are characterized by three spaces: joint space, configuration space, and task space. Joint space characterizes the motion of linear actuators that drive the robot backbones; configuration space allows for a complete representation of the robot kinematics; task space allows for characterization of the 6-DOF position and orientation of the end-effector. Fig. 2 gives a visual representation of the configuration space variables. For each continuum segment, we use two configuration space variables \( \theta \) and \( \delta \) which describe the bending angle and the angle characterizing the plane in which the continuum segment bends, respectively. The insertion of the arm, \( b_0 \), and the \( x \) and \( z \) positions of the five-bar linkage, \( b_{1x} \) and \( b_{1z} \), control the position the base of the continuum segments. These variables form a robot configuration variable \( \Psi \):

\[
\Psi = [b_0 \ b_{1x} \ b_{1z} \ \theta_1 \ \delta_1 \ \theta_2 \ \delta_2]^T (1)
\]

The instantaneous kinematics are solved in (2), using the Jacobian \( J_{x\Psi} \) mapping configuration space and task space velocities as defined in [10]. Following a resolved rates control method, the desired configuration space velocity \( \hat{\Psi} \) is solved based on the desired task velocity \( \dot{x} \):

\[
\dot{x} = J_{x\Psi} \Psi \Rightarrow \hat{\Psi} = W^{-1}J_{x\Psi}^T (J_{x\Psi}W^{-1}J_{x\Psi}^T + \epsilon I) \dot{x} (2)
\]

The configuration space velocity is integrated to determine the current configuration variables. The configuration variables are directly mapped to joint space variables by use of inverse kinematic relationships with actuation compensation and a coordination control module. A PID controller is then used to control joint positions \( \mathbf{q} \).

This redundancy resolution formulation was shown earlier in [10]. We note that in (2), a weighted least norm solution is used to solve for the joint velocities. The weight matrix \( W \) is a diagonal matrix that is used to prevent the robot from reaching its kinematic joint limits. It is also used to prioritize the motion of the base of the robot over motion of the continuum segments, which takes advantages of the stiffness of the parallelogram linkage during forceful environment interaction.

B. Task Space Controller

For a simple environment exploration task (point contact), there is no need to restrict the full orientation of the robot end-effector, so only a select portion of the task space velocity is commanded. Assuming the IREP is placed horizontally, three cartesian velocities and a single degree of rotational velocity \( \omega_y \) around the vertical axis (y) are commanded, describing a four degree of freedom task. The specifics of this task are described below. The task subspace velocities, \( \dot{x} \), are converted to configuration space velocities by combining translational Jacobian and the y-axis row of the orientation Jacobian:

\[
\dot{x} = \begin{bmatrix} \dot{p} \\ \dot{\omega}_y \end{bmatrix} = \begin{bmatrix} J_{p\Psi} \\ J_{\omega_y\Psi} \end{bmatrix} \hat{\Psi}, \quad \dot{x} \in \mathbb{R}^4 (3)
\]

\( J_{p\Psi} \) designates the rows of the Jacobian relating to cartesian velocity, and \( J_{\omega_y\Psi} \) the row relating to angular velocity about the robot base’s y axis. Originally, only Cartesian position was controlled; the control of \( \omega_y \) was added after early experiments in which side collision between the base of the end-effector and the anatomy was observed.
To control the orientation of the robot tip for the exploration task, we define an auxiliary frame \( \{ \hat{u}\hat{w}\hat{v}_g \} \), as shown in Fig. 3. This frame has its \( \hat{w} \) axis along projection of the local tangent to the desired motion path onto the horizontal plane, its \( \hat{u} \) axis along the cross product between \( \hat{w} \) and the upward-pointing vertical axis, and its \( \hat{v} \) axis along the downward-pointing vertical. An angle \( \gamma \) is defined as the angle between the gripper axis \( \hat{z}_g \) and the \( \hat{v} - \hat{w} \) plane. To facilitate the calculation of \( \gamma \), we define a projection matrix \( \Omega_{uw} \) to create a projection of \( \hat{z}_g \) onto the \( \hat{u} - \hat{w} \) plane, designated as \( \hat{z}_g \):

\[
\hat{z}_g \triangleq \Omega_{uw}\hat{z}_g, \quad \Omega_{uw} \triangleq I - \hat{v}\hat{v}^T
\]  

(4)

By replacing \( \hat{z} \) with \( \hat{x} \) and \( J_{z\psi} \) with \( J_{z\psi} \) and using (2), a reduced-dimension redundancy resolution is solved for \( \hat{\psi} \). The cartesian velocity, \( \hat{p} \), is commanded as a linear function of position error with a maximal velocity limit. To calculate the desired rotation of the end-effector we keep \( \hat{z}_g \) in the \( \hat{v} - \hat{w} \) plane by minimizing \( \gamma \) to prevent the organ collision problem mentioned above. This is controlled by rotation about the \( \hat{v} \) axis, so only one degree of freedom needs to be commanded for rotational motion, leaving the other degrees free for redundancy resolution or to avoid joint limits and increase the effective workspace of the robot.

The angular speed \( \omega_y \) to minimize \( \gamma \) is specified using a proportional gain \( k_\gamma \):

\[
\omega_y = k_\gamma \sin (\gamma)
\]  

(5)

While \( \hat{u} \), \( \hat{v} \), and \( \hat{w} \) can be defined in the moving frame of the robot with orientational velocity calculated in the end-effector frame by making use of the body Jacobian of the robot, for our experiments it was kept in the base frame of the robot aligned with the planned raster trajectory. For this paper, these axes are aligned with the base frame of the robot.

C. Admittance-Based Hybrid Force/Position Control

Fig. 1 shows the hybrid force-position controller used for force-controlled exploration. This control framework is a modification of the method presented in [8] to use an indirect admittance controller. A simple PI controller is used to calculate \( \delta f \) based on the errors between the reference and current measured force. Using the inverse task space stiffness, a task space velocity is generated.

\[
K^{-1}_{x} \delta f = \dot{x}_f
\]  

(6)

The stiffness matrix, \( K_x \) can be thought of as the combination of the robot end-effector stiffness in series with the environment stiffness. This stiffness acts as an admittance gain which determines the velocity of the robot depending on the error in the force controller. For this paper, a constant stiffness matrix was used for simplicity of control.

This admittance-based hybrid force/position controller has two main benefits over [8] which relies on robot joint stiffness. When combining flexible continuum segments with relatively stiff joints of the parallel linkage and insertion stage, it is difficult to model and adjust joint stiffnesses to achieve coordinated motion of the robot. Additionally, combining the force and position controllers in task space, allows for a unified redundancy resolution framework which is used to avoid joint limits and can be adapted to execute other subtasks in a straightforward manner.

A hybrid force-motion controller with task decomposition as proposed in [12] is used to explore the environment. Commands are formulated as the sum of orthogonal force and motion directions, controlled by separate force and motion controllers. Orthogonalization is achieved via the projection matrices \( \Omega_m \) and \( \Omega_f \) used to project the task-space errors in motion and force directions, respectively:

\[
\Omega_f = \begin{bmatrix} \hat{n}_c\hat{n}_c^T & 0 \\ 0 & 0 \end{bmatrix}, \quad \Omega_m = I - \Omega_f \quad \begin{bmatrix} \hat{p} \\ \dot{\hat{p}} \end{bmatrix} = \Omega_m \hat{x}_m + \Omega_f \hat{x}_f
\]  

(7)

where \( \hat{x}_m \) and \( \hat{x}_f \) are the desired end effector speeds to close the errors in the motion and force control loops, respectively, and \( \hat{n}_c \) is the contact normal along which we control force. The next important question is how to define the contact normal \( \hat{n}_c \) during blind exploration of an unknown organ.

D. Force Control Direction Update

To traverse non-flat environments before a model is generated, it is necessary to update the force control direction of the hybrid controller during task execution. In a known environment, it is simple to define the force control direction as the local surface normal direction and the motion direction according to (7). However, when performing blind exploration where the robot does not know the environment model, the force control direction \( \hat{n}_c \) must be updated online. The method presented here echoes that developed in [4]. The outline of the frames used in our update framework is shown in Fig. 3.

The nominal force control direction is estimated as the current direction of the vector describing the force felt on the robot, \( f \). The forces are fed through a 1KHz 25-point moving average to reduce noise and prevent sudden changes in the control direction. We restrict the force controller to only
act in the $\hat{v}$-$\hat{w}$ plane of the frame defined in Fig. 3 to prevent forces in a transverse direction to the desired motion trajectory from pulling the robot off course. This is achieved with the use of a projection matrix $\Omega_{vw}$, defined similarly as in (4), replacing $\hat{v}$ with $\hat{u}$. The control direction is calculated as:

$$\hat{n}_c = \Omega_{vw} \frac{f}{||f||}$$  (9)

The above estimate of $\hat{n}_c$ was saturated to prevent it from tilting more than $60^\circ$ relative to the vertical. This limitation was applied to reflect a $a$-priori guess of the steepest slope in organ geometry. Future work should include an update for simultaneous friction estimation while interacting with unknown flexible geometry.

**E. Mixed Feedback Controller for Closed Loop Control**

The IREP was equipped with a magnetic sensing coil to provide feedback about the end-effector tip position during robot-organ interaction. While geometric calibration attempts may help decrease kinematic uncertainty in free space, a full model including large deformations due to environment contact has yet to be developed. Therefore, a “mixed feedback” controller was implemented to provide a desired motion command that is computed based on an internally-updated robot Jacobian and externally-updated position measurements.

The task description in the trajectory planner and the task space error calculations were all performed using measurements from the tracker to close the loop and calculate the desired configuration velocity as per (2). After the configuration space velocity was computed, commands were sent to the joint-level motors using the robot’s inverse kinematics. The configuration variables were integrated based on their commanded velocities to update the Jacobians at the next time step. We refer to this framework as a “mixed” controller because the magnetic sensor measurements do not estimate or update the pose of the robot in configuration space, but still drive the desired control velocity in task space.

Free-space trajectory following experiments were carried out to characterize the performance of the mixed feedback controller. The robot was commanded to follow a circle under both mixed feedback control and using forward kinematics to update the robot pose. As shown in Fig. 4, the mixed feedback controller reduced trajectory-following errors, calculated as the distance between each point saved by the sensor during the scan and the closest point along the circular trajectory. Errors are reported for a sampling frequency of 125 Hz without any filtering. By adding the mixed feedback control, the root mean square (RMS) errors were reduced from 1.89 mm to 1.12 mm in the circle tracking task. The magnetic tracker itself has significant noise: without any motion, we calculated an RMS noise level of 1.41 mm in free space. Our measurements showed the sensor noise was larger in the vertical direction, which aligns with the trajectory direction in the side regions of the trajectory in Fig. 4. This alignment of noise and trajectory direction explains how the trajectory-following error (1.12 mm) is smaller than the norm sensor noise (1.41 mm).

**III. ORGAN EXPLORATION EXPERIMENT**

The experimental setup can be seen in Fig. 5. A phantom kidney created out of molded silicone is mounted onto a plastic base which is slanted in two non-parallel planes to deform the organ. The silicone kidney was fabricated by casting liquid silicone rubber (Ecoflex 00-30) onto a 3D printed mold. The mold geometry was used to define an a priori map of the undeformed organ geometry. The base is affixed to an ATI Gamma force sensor. An Ascension 3D Guidance trakSTAR magnetic tracking system is used to measure the position of the end-effector of the robot.

The control framework introduced above is used to carry out force-controlled exploration of the organ. A raster path in the base plane of the magnetic tracker is used to create a desired trajectory for the robot to follow. The organ was brushed with glycercin to provide lubrication to mimic the fluids found in a surgical setting. A constant force of 0.3 Newtons was commanded to the robot throughout the scan. Once the scan of the organ has been completed, the measurements from the magnetic tracker are used to perform a deformable registration from an a priori scan of the organ to the explored data.
The raster scan was aligned along the major axes of the magnetic tracker, which also correspond to trajectories that largely follow either an "uphill" or "downhill" direction relative to the silicone organ. This keeps the plane of motion aligned with the major required directions of force control. The results of this scan are shown in Fig. 6.

The total scan time for the front of the organ, covering an approximately 5 cm x 3 cm polygon, was approximately 19 minutes. The scan time can be decreased; less dense results with an increased trajectory velocity obtained similar results in less than 10 minutes. Even this is a relatively long scan time: further work will need to be done to decrease scan time to achieve clinically viable scan methods for large areas. For smaller areas, this framework can be used for semi-automation of regulated palpation of specific anatomical regions for further exploration. Such areas may be defined by expert user input or areas obscured by blood or other fluids that may have positional uncertainty when scanned by vision or other imaging modalities.

A. Organ Deformable Registration

Fig. 6 presents the registered data. The a priori model is deformably registered to the to the magnetically tracked exploration data using a point-based deformable registration method, coherent point drift (CPD) [13]. To compensate for the noisy position measurements of the magnetic sensor, a zero-phase moving average filter of 15 points was applied to all the scan data. In addition, since there were instances when the robot lost contact with the organ, any points where measured contact force fell below 0.15 N were removed from consideration in the registration dataset.

The CPD algorithm is based on deforming points in one point cloud to positions within a second point cloud, which makes formulating an inverse transform difficult. Since it is desired to perform analysis and task execution in the magnetic tracker frame, the a priori scan of the organ must be designated as the "moving" data set, and the magnetic tracking scanned results from the robot as the "target" data set. Since correspondence is required for each of the points in the moving set, we trimmed the a priori model to be approximately the same size and shape as the explored data. Since the algorithm regularizes for deformation energy to reduce overfitting, the trimming does not need to match the explored region exactly, but this manual step in the registration algorithm can introduce a measure of subjectivity into the registration process.

B. Ground Truth Comparison

In order to characterize the errors in the registration, we used a FARO Fusion laser scanner to obtain a ground truth measurement of the deformed organ geometry. Spherical fiducials were placed in the magnetic tracker workspace and scanned with the laser scanner and a tracked probe containing an electromagnetic marker. These fiducials were used to register the frame of the laser scanner to the frame of the magnetic tracker. A small scaling factor between the two measurement systems was found to be necessary to reduce the registration error.

With the registration between the laser scanner and the electromagnetic tracker computed, the deformed scan and the laser scan can be compared directly as shown in Fig. 7. Comparing the scans, there was an average RMS error between the laser-scanned surface and the deformed a priori model of 1.75 mm. If a rigid registration is used in place of the deformable CPD algorithm, this error increases to 2.33 mm. These errors include registration errors from the laser scanner to the magnetic tracker. This is comparable to results estimated when using a laser-scan endoscope system with errors of 1-1.5 mm in a laparoscopic context [2].

While the estimated surface normal used for control, \( \hat{n} \), was projected and filtered to improve performance, it is also useful to see how the direction of the force vector relates to the direction of the surface normal. The angular errors between the unit norm vector of the force felt during the organ scan and the normal vector of the closest point on the registered point cloud from the laser scan were calculated, and the RMS error was found to be 11.88 degrees. This shows that, while not exact, for a well-lubricated surface, the force direction vector is close to the surface normal direction.

IV. CHALLENGES AND FUTURE WORK

There are a number of challenges that will need to be overcome to enable better force-guided robotic palpation and
to enable the extraction of more information from such procedures.

There were instances where the robot lost contact with the organ during scanning. One particular cause of this is the elastic energy held in both the robot and the organ. When moving up very steep regions of the phantom, the force controller is pushing in a largely horizontal direction. This bends the continuum structure of the robot which then can "pop" out of the organ as it crests the hill, straightening significantly. The robot subsequently returns to the scanning trajectory, but a more complete compliance framework will need to be formulated and integrated into a control framework to compensate for this stored energy and to prevent rapid changes in robot shape.

While our method was able to traverse even steep areas of the organ, the trajectory followed by the robot often had errors from the planned raster pattern as it moved up and down the surface. Lack of friction compensation and the flexible nature of the environment contributed to these errors. A more robust exploration framework should estimate relevant parameters to compensate for these effects and reduce these errors during blind exploration.

One important future contribution is the use of intrinsic force sensing during exploration of deformable geometry organs using surgically deployable systems, which will remove the need for the under-organ force sensor which is not clinically feasible. Future work in this area will include better friction estimation models and compensation techniques for online force sensing.

Additional important areas for exploration include organ stiffness estimation, methods for capturing more complicated physical organ properties, and on-line updates of geometry or registration parameters. Online estimates of the deflected robot shape and identification of multi-point contact will also be useful for broader applicability of this method.

V. CONCLUSION

This paper has presented the feasibility of continuum robots to scan unknown geometry elastic environments and to form updated geometry models of the environment using deformable registration. An updated hybrid force-motion and admittance controller for a continuum robot was introduced to improve robot control efficacy for this task. The coherent point drift deformable registration algorithm was shown to be able to update an a priori environment model using the exploration data for the execution of further tasks requiring an updated model such as telemanipulation virtual fixtures or semi-autonomous ablation along a path or in a patch. Results of the deformable registration suggest that force-controlled exploration data may be feasible for updating the geometry of the environment and that the error in estimating the surface normal was less than 12°. Future work will include integration of intrinsic force sensing capabilities and estimation of friction, stiffness, or other characteristics of the explored organ during force-controlled palpation.

ACKNOWLEDGMENT

This work was supported by NRI Large grant IIS-1327566

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