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RAVEN-S: Design and Simulation of a Robot for Teleoperated Microgravity Rodent Dissection Under Time Delay

Andrew Lewis*[1,2], David Drajeske[2], John Raiti[1,2], Angelique Berens[1], Jacob Rosen[2,3], Blake Hannaford[1,2]

***Abstract*— The International Space Station (ISS) serves as a research lab for a wide variety of experiments including some that study the biological effects of microgravity and spaceflight using the Rodent Habitat and Microgravity Science Glovebox (MSG). Astronauts train for onboard dissections of rodents following basic training. An alternative approach for conducting these experiments is teleoperation of a robot located on the ISS from earth by a scientist who is proficient in rodent dissection. This pilot study addresses (1) the effects of extreme time delay on skill degradation during Fundamentals of Laparoscopic Surgery (FLS) tasks and rodent dissections using RAVEN II; (2) derivation and testing of rudimentary interaction force estimation; (3) elicitation of design requirements for an onboard dissection robot, RAVEN-S; and (4) simulation of the RAVEN-S prototype design with dissection data. The results indicate that the tasks' completion times increased by a factor of up to 9 for a 3 s time delay while performing manipulation and cutting tasks (FLS model) and by a factor of up to 3 for a 0.75 s time delay during mouse dissection tasks (animal model). Average robot forces/torques of 14N/0.1Nm (peak 90N/0.75Nm) were measured along with average linear/angular velocities of 0.02m/s / 4rad/s (peak 0.1m/s / 40rad/s) during dissection. A triangular configuration of three arms with respect to the operation site showed the best configuration given the MSG geometry and the dissection tasks. In conclusion, the results confirm the feasibility of utilizing a surgically-inspired RAVEN-S robot for teleoperated rodent dissection for successful completion of the predefined tasks in the presence of communications time delay between the ISS and ground control.**

I. INTRODUCTION

NASA has been using the Rodent Habitat and Microgravity Science Glovebox (MSG) on board the International Space Station (ISS) to study the biological impact of microgravity and effects of spaceflight since 2014 [1]. Applied Dexterity was given the task of appraising the feasibility of an onboard RAVEN robot for performing dissections from Earth by teleoperation as an alternative to performing manual dissections by time-constrained astronauts [2]. NASA's project goal was to provide a system that could provide dissected tissue with quality equivalent to manual dissections while subject to time delays up to 5 seconds.

The RAVEN II research platform [3] was developed with functional requirements derived from sensorized, *in vivo*, manual laparascopic porcine surgical procedures [4]. The range of procedures and large pool of expert participants informed the volume, velocity, and force requirements for both RAVEN I and RAVEN II.

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[1]University of Washington, 185 E Stevens Way NE AE100R, Seattle, WA 98195 (alewi, jraiti, berens, blake)@uw.edu
[2]Applied Dexterity, 4000 Mason Rd, Seattle, WA 98195 david@applieddexterity.com
[3]UCLA, Los Angeles, CA jacobrosen@ucla.edu

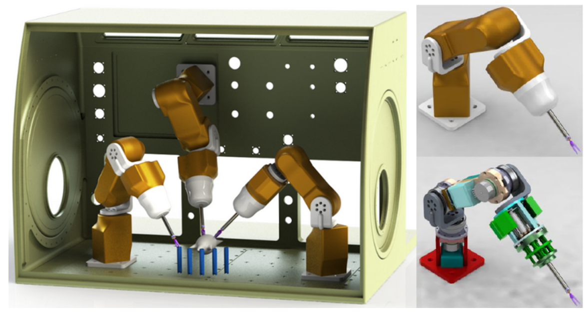

Fig. 1: The RAVEN-S, designed for remote teleoperation of rodent dissection on board the International Space Station. Shown in 3 arm configuration with and without protective covers.

Teleoperation in the presence of time delay for space applications has been studied by Sheridan and others since the 1960s [5]. More recently, the effects of time delay have been studied on the performance of telesurgery [6]. Lum *et al.* specifically investigated the effects of time delay on teleoperated performance of standard laparoscopic surgical training tasks on the RAVEN I with delays up to 1s [7]. Rayman *et al.* used a Zeus surgical robot to perform dry and wet lab telesurgery feasibility experiments at remote sites in Canada with delays up to 1s and concluded that maximum tolerable delays for telesurgery are around 600 ms [8].

Four activities are described in this paper: (1) **time delay studies** of surgical skill tasks and rodent dissections to validate the concept of teleoperated ISS dissections; (2) derivation and testing of rudimentary **interaction force estimation**; (3) elicitation of **design requirements** for an onboard dissection robot; and (4) **simulation of prototype design** with dissection data.

II. METHODOLOGY

A. Time Delay Studies

In order to minimize the number of rodent dissections performed and provide a full understanding of dissection feasibility at a wide range of delays, an experimental model of rodent dissection was required. It was hypothesized that standard surgical training tasks could be analyzed individually at a range of time delays and then used to extrapolate dissection times from only a few dissections at zero and low delay.

Two Fundamentals of Laparoscopic Surgery (FLS) tasks [9] were identified as representative of primary dissection tasks: the peg-transfer and the precision cutting tasks. The

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peg-transfer task approximates manual acquisition, handling, and depositing of tissues, while precision cutting approximates the incision of the abdomen and skinning and removal of the hind limbs. The scale of the FLS tasks and tools required are similar to those of rodent dissection.

Experiments were performed with a telesurgery setup consisting of a customized Mantis Duo bimanual 7-DOF controller (Mimic Technologies, Seattle, WA) and a RAVEN-II (Applied Dexterity, Seattle, WA). The RAVEN arms were equipped with expired da Vinci Si tools (Intuitive Surgical, Sunnyvale, CA). Stereo video was provided via HD 3D Panasonic Camcorder connected to a Panasonic 3D TV. Time delay was simulated with constant time delay buffering functionality inserted as a man-in-the-middle node as developed for and described in [10].

Participants in these experiments were limited to the first author of this paper due to the time required to achieve teleoperation proficiency. This user had already surpassed the sufficiency requirements of a previous study [11].

1) FLS Peg-Transfer task procedure:

- Starting with the dominant hand, grasp and lift a block
- Transfer the block to non-dominant hand
- Place block on peg of opposite side
- Repeat until all blocks are on opposite side
- Repeat in reverse until all blocks are on original side

2) FLS Precision Cutting task procedure:

- Use non-dominant hand with grasper tool to provide tension across the marked circle
- Using scissors in dominant hand, follow the marked circle and completely remove the inside of the circle
- Re-position tension hand and change cutting direction as necessary

Two Large Needle Driver tools were used for the peg-transfer task and one Monopolar Curved Scissor tool was used in conjunction with a needle driver for precision cutting tasks and all dissections.

Only 3 blocks were used in the peg-transfer task instead of 6 in order to increase the quantity of trials. Transfer experiments were conducted at delay steps of 250 ms from 0-1000 and 500 ms from 1000-3000 with decreasing number of trials with time delay (24 trials at 0 delay to 3 trials at 3000 ms delay, with 142 total trials). Precision cutting was performed at steps of 250ms from 0 to 1000 and at least 4 trials at each delay.

Task Time Increase (TTI) factor describes the increase in task completion as a function of time delay. This factor was calculated for both transfer and cutting tasks by dividing completion times by zero delay completion times. A linear model of the TTI could then be used to extrapolate rodent dissection times from a smaller data set.

3) Thawed Mouse Dissection: Several frozen mice were thawed and dissected using the following procedure, which was modeled on the dissection procedure of NASA's Rodent Research Mission 1:

1) Incise the abdomen, retract abdominal wall (peritoneum & rib)
2) Isolate liver, cut free, and place in collection vial
3) Isolate spleen, cut free, and place in collection vial

An additional participant was added to rodent dissection experiments due to experience with manual rodent dissection and significant surgical training. This participant underwent about an hour of training at varying delays on the tasks described above. Frozen mice were obtained from a nearby pet store and left at room temperature to thaw just prior to the experiments. Each participant completed 2 complete dissections at zero and 500ms delay and 1 dissection at 750ms. 3D videos of each procedure were collected and then reviewed in order to measure task completion times.

B. Interaction Force Estimation

In order to characterize the requirements for teleoperated dissection, a force estimation model was derived for the RAVEN II. A simple model of interaction forces was developed with the goal of a general understanding of forces required for robot design. Commanded motor torques for the 3 positioning motors on each arm were recorded at 50 Hz. The gravity compensation component [12] of the command current was subtracted to isolate the task-specific currents. These currents were then multiplied by the motors' torque constant, gearbox ratio, and joint cable coupling ratio to calculate joint torques.

A force-reporting frame was defined where the x-axis was parallel with the body of the rodent and the z-axis normal to the table. With the simplifying assumptions that: (1) the second joint ("elbow") remained nearly perpendicular to the first joint ("shoulder") and (2) the third joint ("insertion") remained nearly perpendicular to the table, the simple force estimation model for rodent-based interactions is as follows:

$$F_x \approx \tau_1 / l$$
$$F_y \approx \tau_2 / (l * sin(52°))$$
$$F_z \approx F_3$$

where τ_1, τ_2, and F_3 are the shoulder joint torque, elbow joint torque and insertion joint force, respectively, and l is the distance between the remote center and the tool tip. The angle offset between the elbow axis and the tool shaft is set by the link structure at $52°$.

Fig. 2: Left: The FLS peg-transfer task with 6 colored blocks that must be moved from side to side with handoffs. Right: The FLS precision cutting task where the participant must cleanly remove the marked circle of gauze as quickly as possible.

This estimation is sufficient for general force magnitudes in a specific area of the RAVEN II workspace, and the dissection area was positioned to enable these calculations.

The estimation was validated by grasping the free end of a calibrated spring in the workspace and performing sinusoidal motions in each of the frame's axes. The difference between the start position and the current position was multiplied by the spring constant to provide a ground truth force magnitude.

Tool interface torques were calculated from the commanded motor torques multiplied by the gearbox and cable-coupling ratios. The gravity component of the tool DOFs is negligible.

C. Dissection Design Requirements

Once feasibility was established, functional requirements for a dissection-specific robot platform were derived from further rodent dissections using the RAVEN II with two omega.7 controllers (Force Dimension, Nyon, Switzerland). The procedure was expanded to include removal of the hind legs: cutting of skin around the base of the leg; pulling the skin over the foot and off the leg; and then cutting through the hip or hip ligaments in order to deposit the leg in a collection vial.

The functional requirements to be characterized were: tool tip interaction forces, tool tip velocities, tool interface capstan torques, and tool interface capstan velocities. Only the tool interface characteristics were required because the design of the RAVEN-S tool mechanisms would be nearly identical to the RAVEN II tools.

Two mice and one rat were thawed and dissected with no time delay. It was hypothesized that there would be a difference in the forces applied by the robot during teleoperation under time delay. Thus, one additional mouse procedure was performed with one second of delay.

D. RAVEN-S Design and Simulation

Since the RAVEN II arms were designed for laparoscopic surgery, a new design was needed to meet the needs of the space environment and related applications as an ISS resource, as well as the size constraints of the MSG and Life Sciences Glovebox (LSG). Furthermore, the cable drive design of the RAVEN-II introduces unneeded mechanical complexity and requires specialized maintenance training.

Three conceptual arm designs emerged for further development (Fig. 3), referred to as Surgical Cockpit-style, RAVEN-Style, and Red Base Arm. Each design was modelled to the point where it could be feasibly built and each motor and gearbox were chosen to meet the force and velocity requirements outlined below. Each design provides 3 Degrees Of Freedom (DOF) positioning. The Cockpit-Style arm also provides a 3 DOF orientation gimbal for a 2 axis tool, while the other two designs accommodate a traditional 4 DOF RAVEN-style tool for orientation and grasping.

The following unweighted metrics and desired features were evaluated objectively or subjectively with consensus from the authors for each design. The Red Base Arm exhibited the most desirable fit for teleoperated and autonomous MSG tasks. The starkest advantages are bolded.

- Ease of MSG Loading
- **Workspace size**
- Stowage Volume
- Manual Tool Change
- **Auto Tool Change**
- Ease of Repair
- Interchangeable Arms
- **3+ Arms**
- Mass
- Novelty
- MSG Visualization
- Tool Torque

The primary link lengths of the RAVEN-S design were chosen to reach at least 75 mm past the primary workspace for rodent dissection. From this requirement, worst-case joint loads were calculated from the requirements and used to drive gearbox and motor selection. Since the first two axes have equivalent maximum moment arms, they were designed with the same motor and gearbox. Furthermore, advantages of repeated equipment outweighed the small weight and cost savings of a different motor gearbox pair for the third joint. The gearbox chosen is the Harmonic Drive CSG-14-100-2UH-LW, a single stage gearbox with a reduction of 100:1. The nearly negligible backlash results in a theoretical worst-case accuracy of less than 0.1 mm. The motor paired to this gearbox is the 70 Watt brushless Maxon EC-45 with integrated encoder. Once the motors, gearboxes, and motor controllers were chosen, the link lengths and structure were then fine-tuned to minimize mass, volume and moment arms. Each link is encased in protective covers that will be smooth and easy to clean with disposable wipes after missions.

The links use repeated components to minimize cost and enable efficient repair strategies. Each arm is interchangeable. A spare arm could be mounted in the workspace for performing procedures requiring three arms, or reserved as a "cold spare" within the workspace. With a small set of common tools, key components can be swapped for onboard

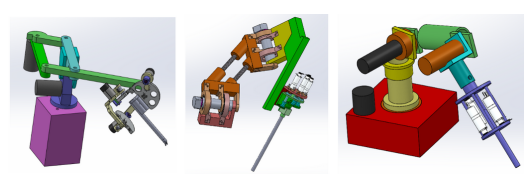

Fig. 3: Initial design candidates for the RAVEN-S. From left to right: the Cockpit-style 5 DOF arm with 2 DOF tool; the RAVEN-style arm with spherical remote center mechanism; the serial Red Base Arm.

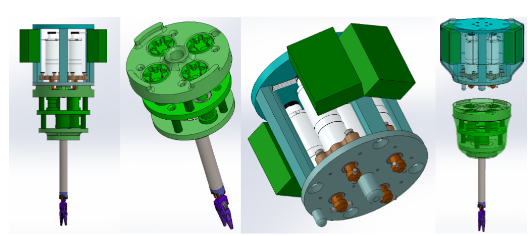

Fig. 4: Left to right: the shortened RAVEN grasper attached to motorized interface; interface spindles of the tool and guide-pin holes; motorized tool link of the RAVEN-S arm with spring-loaded motor attachments, motor controllers, and guide pins; and the tool aligned for attachment.

repair. Each arm plus tool has an estimated mass of 4 kg.

The RAVEN-S tools (Fig. 4), including graspers and scissors, are based on the patented RAVEN II tool designs [13]. It is important for the crew to be able to replace tools one-handed. The RAVEN-S tools have a direct motor connection through an axially-compliant connection interface. Together with guiding rods and spring-loaded latch (not shown), the interface design allows quick replacement while ensuring high tool torques and accuracy. Green motor controllers are shown on either side of the tool motor pack.

Analytic inverse kinematics and inverse force estimation models were derived for the positioning joints of the RAVEN-S design, and the two arms were given an estimated transform offset from the workspace of the recorded rodent dissections. The recorded positions were then used with the inverse kinematics model to calculate the expected joint angles and joint velocities of the RAVEN-S while performing dissections. Recorded force trajectories were used to calculate the instantaneous joint torques of the RAVEN-S, which were multiplied by the instantaneous motor velocities in order to calculate the electrical motor power requirements of the RAVEN-S design.

III. RESULTS

A. Time Delay Experiments

The linear model of transfer Task Time Increase (Fig. 5) follows the average performance until 2000 ms of delay, at which point the increase factor appears to level off. Between 1000 and 2500 ms, the transfer task appears to be more susceptible to performance impacts with an increase factor peaking near 11. Thawed rodent dissection TTI (Fig. 6) was almost entirely bounded by the TTI for the FLS tasks. The TTI for abdominal incision and overall dissection completion for the two participants was negative.

Table I compares each step against time requirements provided by NASA biologists. None of the trials completed the abdomen incision within the required time, but liver and spleen collection were both within the required time at all tested delays. Completion times were predicted by multiplying the zero-delay times with the TTI of either cutting tasks (abdomen) or the average of the two models(collections) to account for the combined cutting and manipulation nature of the task. The predictions as presented show that total dissection time would fall within requirements below 1000 ms of delay.

B. Force Estimation Model

Current based estimations of forces applied at the RAVEN II end effector match closely to estimated spring forces. Figure 7 shows forces at the tool tip during left-to-right motion. Comparisons between spring forces in the remaining axes show similar agreement in magnitude.

C. Rodent Dissection Requirements

End effector forces applied during rodent dissection show little variation when performed with time delay or with a slightly larger animal (rat) (Fig. 8). Forces along the tool shaft are about 60% higher than in the perpendicular plane.

Table II summarizes the requirements for a teleoperated rodent dissection robot from these experiments.

D. Design Simulation and Evaluation

Each of the six RAVEN-S positioning motors was found to be within the published velocity and power specifications of the chosen motors and gearboxes for the recorded rodent dissections for peak and RMS values. Furthermore, the joint angles stay within a reasonable volume within the glovebox for the recorded dissections.

IV. DISCUSSION

A. Time Delay Experiments

Average TTI factor for the two studied sub-tasks increases linearly with increasing time delay, furthermore: the TTI increased greater for the manipulation task than for the cutting task, and TTI for the manipulation task has a much smaller slope after 2000ms of delay.

The difference between TTI increase is likely due to differing task characteristics. The cutting task requires the non-dominant hand grasp and pull in a relatively wide range of grasping areas and pulling vectors, while the dominant hand, once inside the initial snip, follows a marked trajectory without much repositioning or reorientation. In contrast, each peg transfer requires many precise placements during pickup, transfer, and drop-off. Each of these positioning steps could introduce a greater effect on the completion time by increased time delay. Aligning both graspers in free space

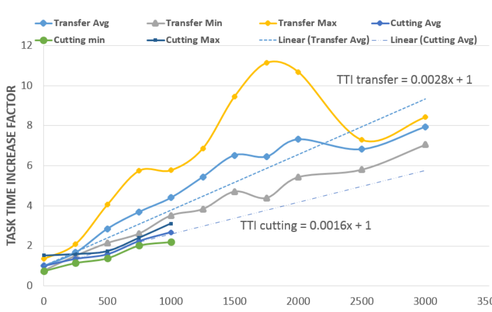

Fig. 5: Task completion time increase relative to non-delayed average task completion times for FLS Peg Transfer and Precision Cutting tasks. The models of the TTI factors for constant time delay in ms are shown.

Fig. 6: Task completion time increase of individual dissection tasks as a factor of non-delayed average task completion times. The average time increase factor for cutting and transfer tasks from Fig. 5 are included.

TABLE I: Predicted performance of rodent dissection tasks with time delay

Step	Measured Time (0 delay)	Multiplier	Target Time	Measured		Predicted		
				500ms	750ms	1000ms	1500ms	2000ms
Abdomen	442	0.0016	180	311	233	1148	1501	1854
Liver	50	0.0022	240	70	62	160	215	270
Spleen	34	0.0022	240	58	106	107	144	181
Total Procedure	525		660	438	400	1415	1860	2305

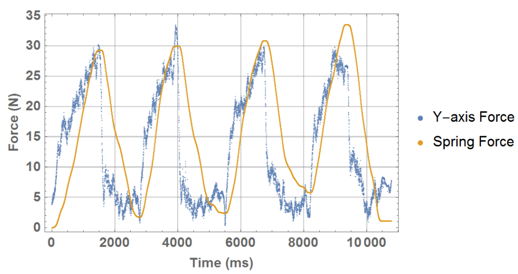

Fig. 7: Estimated force of the RAVEN end effector along a single axis and force applied to the end effector by a spring.

TABLE II: Velocity and force requirements for rodent dissection

	RMS	Peak
Applied Force (X-Y)	10 N	80 N
Applied Force (Z)	18 N	100 N
Velocity (X-Y-Z)	0.02 m/s	0.1 m/s
Tool Interface torque	0.1 Nm	0.75 Nm
Tool Interface velocity	4 rad/s	40 rad/s

during peg transfer presents extra synchronization difficulty compared to circle cutting.

At high time delays (greater than 2000 ms), a change in approach is noticed from the move-and-wait strategy of both arms described in the literature to a "move-then-move" strategy. In this new strategy, the participant was able to make a short trajectory with one hand, switch focus to the other hand to perform another move, and then switch focus back at about the time that the initial tool had completed its movement in order to start again. It is believed that this focus switching was able to gain back task time otherwise lost to move-and-wait schemes at shorter delays. This has only been noted in one participant, but could describe another regime of performance at extreme time delays unexplored in current literature. This effect was not observed within the cutting task because the trials only included delays up to 1000 ms

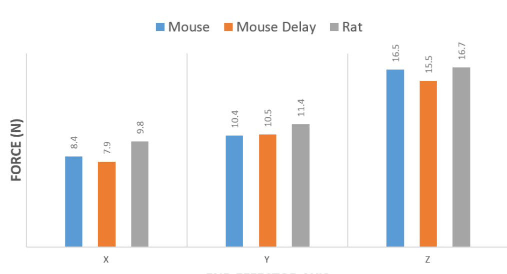

Fig. 8: RMS forces when performing similar dissection procedures on mice (with (orange) and without (blue) 1-second time delay) and a rat without time delay (gray).

and relied less on continual bimanual operation.

Modeling the total dissection task as a combination of cutting and manipulating is shown to provide an upper bound of completion time under time delay. The abdominal opening TTI falls underneath the average cutting TTI while both of the organ collection TTIs remain below the average manipulation TTI. The small number of trials and participants prevent further observations as training effects contributed heavily with increasing time delay. TTI less than one is seen as experienced dissection times are divided by untrained dissections at zero delay. Future studies should include an explicit training window in order to separate training data from those used in the TTI denominator.

Modeling of complex procedures with component tasks with empirical TTI factors is a novel approach to determining the feasibility of performing procedures under a range of possible time delays. This approach may determine the acceptable limits of time delay when given specific scientific time requirements for each step. However, the limited number of subjects and dissection trials limits the effectiveness of this analysis. This approach could speed up understanding of complex tasks by reducing the time spent on lengthy, high-cost experiments in favor of shorter, simpler component experiments. Adopting this approach has spared the lives of rodents that would otherwise be sacrificed for modeling of TTI for experiment feasibility.

Finally, these experiments introduce the use of easily obtained frozen rodents as a model for surgical robotics research. These models are less expensive than human cadavers and easier to obtain at higher numbers; they provide more anatomical complexity than butcher-shop animal organs; and they exhibit higher fidelity visual properties and soft tissue interactions than most phantoms. Rodent dissection could provide a rich and medically translatable research area for robotics researchers in the areas of automation, haptics, and computer vision.

B. *Force Estimation and Design Requirements*

The force estimation model presented is expected to be useful for RAVEN researchers investigating force magnitudes during various tasks and could be integrated into real-time safety software to limit applied forces. The estimation was shown to be fairly accurate when compared to the displacement of a spring. However, the phase difference between the spring displacement and the estimated force likely indicates hysteresis in the system. For this reason it is unlikely that this approach on its own could be useful for real-time applications such as direct haptic feedback.

The force estimation model does not account for inertial dynamics of the robot. Modeling of the intertial contributions and friction could more accurately represent the force requirements of the designed robot, potentially lowering the power requirements and therefore the system weight. However, capabilities that may be required of the final system on the ISS may exceed those of the tested procedures, so further optimization may prove detrimental.

Perhaps unsurprisingly, the peak forces exerted during the rodent dissection experiments are similar in magnitude to the requirements to which both the RAVEN I and RAVEN II robots were built [4]. Some aspects of the rodent dissection required considerable force, so the RAVEN II was likely pushed close to the designed maximum or software safety limits. This indicates that thawed rodent cadavers could be a useful analog to *in vivo* experiments for surgical robotics.

C. Design Simulation and Evaluation

Using the recorded dissection data to simulate the performance characteristics of the RAVEN-S provides initial validation of the design process and hardware selection. Higher fidelity models that include robot dynamics and motor performance characteristics would allow for further design simulation such as heat dissipation capabilities during procedures and lifetime calculations for the motor and gearbox. This procedure could also be repeated with varying link lengths or robot kinematics in order to optimize for minimum power usage during dissection procedures.

V. CONCLUSION

This paper demonstrates the use of easily measured and repeated tasks at increasing communications time delays in order to model the feasibility of complex tasks at varying levels of time delay. These tasks were evaluated at delays that have rarely been studied in the telesurgery literature and a new paradigm of "move-then-move" which exploits the nature of some bi-manual manipulation tasks at very high delays has been described. Further work is needed to integrate the comparative difficulty of component tasks and the task being modeled. Furthermore, more subjects need to be recruited for similar studies with a more rigorous training protocol in order to generalize these results.

Organ collection can be completed within the total dissection time dictated by science requirements with up to 750 ms of delay, slightly larger than the tolerable delay described in [8]. The effects of time delay could be mediated with various simulation and visualization techniques described in the literature.

A simple method of force estimation for the RAVEN II robot has been derived and used to characterize the functional requirements of a teleoperated rodent dissection robot. Initial results indicate that there is little difference in the magnitude of applied forces between teleoperated dissections with and without time delays. The estimated forces led to requirements and designs for the RAVEN-S. The design was evaluated using inverse kinematic and force estimation on recorded dissections and validated the kinematic design and component choices.

The RAVEN-S was put forth as part of a comprehensive system proposal in response to a call for an onboard teleoperated rodent dissection resource from the NSF and NASA. In addition to rodent dissections, the authors have discussed the use of RAVEN-S for other scientific missions such as Plant Pathology and the opportunities that having a surgically-inspired robot onboard would provide for future technology demonstrations.

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