2016 IEEE International Conference on Robotics and Automation (ICRA)
Stockholm, Sweden, May 16-21, 2016

User's Task Performance in Two-handed Complementary-motion Teleoperation

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Abstract— **Despite recent advances to improve transparency of teleoperation systems, certain tasks remain difficult and time-consuming when performed via teleoperation. Operators are often required to perform tasks involving multiple degrees-of-freedom (DOFs) requiring great dexterity. To be fully adopted, the speed and ease of teleoperated task performance must be increased. A possibility is to use cooperative manipulation, namely two-handed teleoperation, to allow the two hands of the user to manipulate two master haptic devices in order to control a slave robot with multiple DOFs; the total DOFs of the two masters are equal to the DOFs of the slave. We present the results of a user study that evaluates the performance of a bimanual teleoperation system involving two 3-DOF haptic master interfaces to control a 6-DOF slave manipulator. The two master's motions are complementary. Then, we compare this performance to a single-master/single-slave teleoperation system using 6-DOF master and slave manipulators. In order to compare the users' performance in the two systems, a 6-DOF task experiment is considered. The task performed resembles typical tasks carried out in surgery. The results of our study suggest that DOF decomposition leads to significant improvements regarding task completion time and trajectory tracking for a task which involves following a pattern while maintaining a desired depth.**

I. INTRODUCTION

Telemanipulation of high degree-of-freedom (DOF) systems is challenging when involving the control of all six DOFs simultaneously, namely three for position and three for orientation. It has been shown that operators control certain subsets of the total number of DOFs at a time and switch control between those subsets, implying that simultaneous manipulation of all the DOFs does not necessarily lead to the best performance [1]. Furthermore, in [2], the authors show that the input device has an influence on the allocation of the DOFs. The ultimate goal is to provide users with an easy way of performing dexterous tasks involving translations and rotations through teleoperation systems by observing the influence of the DOF decomposition on the users' performance during the achievement of a certain task.

Optimal distribution of DOFs has been recently studied and the results are sometimes contradictory. Some authors have pointed out that the integration of all the DOFs on the same device improves the performance, while some others have shown that the manipulation of six DOFs requires to split the DOFs between more than one device to achieve better performance. Hinckley et al. demonstrated through a user study that performing simultaneous rotations along three axes is faster with a 3-D input device [3]. By using a docking task, Wang et al. showed that even though the translation and the rotation are performed simultaneously during the manipulation of an object, they are not completely overlapped in time [4]. Malysz and Sirouspour compared a single hand control mode to a translational-rotation mode for which a 2-DOF master haptic device controlled the translation of the slave and a 1-DOF master haptic device controlled the orientation. They demonstrated through a human factors experiment involving a maneuvering task that the single hand control mode had the best performance regarding task completion time. However, the difference between the single hand control mode and the translational-rotation mode was not statistically significant [5].

Two-handed teleoperation is an emerging application of teleoperation systems [6]. Although it has been mostly applied to robotic rehabilitation [7], dual-user haptic training [8] and surgical training [9] [10], a two-handed teleoperation system has been used in [11] to control a redundant manipulator. One master controlled the end effector of the slave robot, whereas a second master controlled the nullspace of a kinematically redundant slave robot in order to avoid collision with obstacles in the task environment.

For our study, participants performed a task that implies the use of both translation and rotation. We investigate a 6-DOF cutting task of a phantom tissue to realistically replicate much of the complexity of a surgical task. We use the same 6-DOF master haptic device for both two-handed and single-handed teleoperation systems by restricting the number of DOFs avalaible to three for the two master interfaces of the two-handed teleoperation system.

To our knowlegde, this user study compares the first time users' performance between cooperative manipulation and single robot manipulation using 6-DOF haptic interfaces. In order to conduct our user study, we have implemented both bimanual and unimanual teleoperation systems that provide force feedback. In order to evaluate the users' performance, we recorded the end-effector position and the task completion time for quantitative analysis. Moreover, we utilized a questionnaire to qualitatively evaluate both systems in terms of accuracy and ease of operation.

This paper is organized as follows. In Section 2, we introduce our motivations and justifiy the utility of cooperative teleoperation. Then, in Section 3 we describe the design of the experimental user study we conducted to examine the users' performance of a cooperative teleoperation system in comparison to a conventional teleoperation system employing only one master interface to manipulate a slave robot. In Section 4, we present the results

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we obtained. Finally, in Section 5 we make conclusions and propose perspectives for future work.

This paper is accompanied by a video which summarizes the experimental study.

II. MOTIVATION

We propose to conduct a user study in order to examine the advantages of cooperative teleoperation over conventional teleoperation in a cutting task in a real environment. The task aims to cut phantom tissue according to a pattern drawn on the tissue. Several studies have investigated how users' performance is affected by haptic feedback and it has been found to enhance the task performance. For instance, haptic devices have been widely used for surgical purposes in order to improve the surgeon's performance during telesurgery [12] [13]. For this very reason, haptic feedback is implemented in this paper to provide the user with a feedback of contact forces between the cutting blade and the phantom tissue. In addition, all the six DOFs are included in the teleoperation system.

In [14], Li et al. studied cooperative teleoperation for a planar peg-in-the-hole insertion task involving two translations and one rotation. They proposed dividing the peg-in-the-hole insertion task into three steps performed consecutively with two different master interfaces. The first master interface would control the rotation of the slave manipulator whereas the second master interface would control the two translations of the slave manipulator. This provides a separation between the translation and the orientation of the manipulated object. For our study, the cutting task is only considered. In this paper, we propose a strategy for the decomposition of the six DOFs required by the cutting task. For this task, the depth of the cutting tool has to be controlled with accuracy inside the tissue while the operator moves the tool along the two other axes. Thus, one master interface controls the z-translation (depth of cutting) and the x and y-rotations (angles of cutting) while another interface controls the x and y-translations and the z-rotation (path of cutting). z denotes the vertical direction while x and y denotes the lateral ones. The cutting task aims to replicate the complexity of the surgical procedures. For instance, the proposed task can be related to the elliptical excision which is used for the therapeutic removal of benign and malignant lesions. In order to succesfully achieve this excision, a jagged edge must be avoided and thus confident strokes from the surgeon have to be performed [15]. If required, this surgery can be carried out via teleoperation, for example to allow the surgeon to be at a different site as the patient. However, to be adopted by the medical community, the slave robot end-effector should replicate the expert movements of the surgeon's hands through easy operation while maintaining precision.

We hypothesize that for the task considered, a separation of the DOFs using the aforementioned strategy may lead to better performance or at least allow to design cheaper system including several low-cost devices with lower DOFs without undermining performance [14][16].

III. METHODS AND MATERIALS

A. Goal

The main goal of the experiments is to evaluate the effect of DOF separation on a teleoperated task. Experiments were designed to compare users' performance between conventional and cooperative teleoperation. The experiments include both visual and force feedback to the user. The main performance measurements recorded were completion time and trajectory tracking. The experiments presented here were designed to address these questions:

- Can users simultaneously control all six DOFs of a master haptic device to perform a 6-DOF task on a remote environment using haptic teleoperation?
- Can a 6-DOF haptic master device be substituted with two 3-DOF haptic master devices without performance degradation?

B. Experiments description

We studied the user performance during the achievement of a task using either a single-handed teleoperation system or a two-handed teleoperation system. The single-handed teleoperation system uses only one master to provide all the DOFs required in the task for the user to simultaneously manipulate the three translations and the three orientations of the slave robot end-effector. The two-handed teleoperation system decomposes the 6 DOFs into 3+3 DOFs. One interface commands two translations (along x and y-axes) and one rotation (along z-axis) whereas the other interface commands two rotations (along x and y-axes) and one translation (along z-axis). By analysing and comparing the data recorded through the user study, we will observe the influence of the DOF decomposition. Speed (task completion time) and accuracy (trajectory tracking) are used to highlight the possible performance differences between the two conditions. A questionnaire filled in by the participants is also a highly valuable source of information to compare the two conditions in term of ease of operation.

C. Apparatus

The system (Fig. 1) consists of the master subsystem and the slave robot. Depending on the teleoperation system involved (unimanual or bimanual), the master subsystem includes one or two High Definition HD^2 Haptic Devices (Quanser, Inc., Markham, Ontario, Canada). This device is a parallel 6-DOF haptic device. The slave system includes a SIA5F 7-DOF redundant robotic arm (Yaskawa Motoman Miamisburg, Ohio, USA), which provides "human-like" flexibility. An ATI Gamma NET force/torque transducer (ATI-IA, Apex, NC, USA) is attached to the end-effector of the slave manipulator. The two HD^2 master interfaces are controlled via a custombuilt Quanser robot controller called Quarc. Matlab Simulink is used for real-time control with Quarc. A robot control program developed in Win7 and running in WinCE was designed to control the Motoman SIA5F robot. The Win7 is linked to the WinCE via a virtual machine. A C++ communication application receives

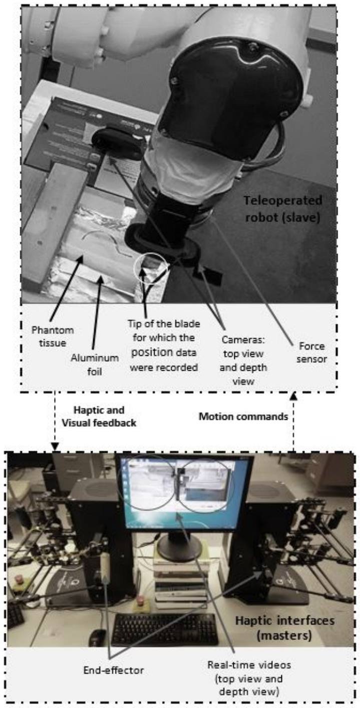

Fig. 1. Bimanual teleoperation experimental setup with the master and slave robots

data from the SIA5F robot control application and relays it to Quarc robot control application via shared memory. It also receives data from the Quarc robot control application and relays that to the SIA5F robot control application. The communication channel is implemented using the Winsock application programming interface over the Ethernet using the UDP protocol at a 1 kHz sampling rate – the same rate as the one used in the Quarc robot control loop. External forces are measured by the Gamma NET force/torque transducer attached to the end-effector of the slave manipulator at a 1 kHz sampling rate. In order to provide enough transparency, the direct force reflection architecture [17] is implemented for both unimanual and bimanual teleoperation systems such that the interaction forces on x-axis and y-axis acting on the slave robot can be accurately fed back to the user. A force feedback gain of 0.5 was used to provide enough forces on the master side while maintaining system stability.

No gravity compensation is used for the HD^2 master interfaces.

A Logitech C270 video camera is attached to the slave robot end-effector to provide visual feedback showing the top of the phantom tissue. Visual feedback of the tool depth is provided by a second Logitech C270 camera facing the side of the transparent phantom tissue.

The entire system runs at 1kHz. However, recorded data could be down-sampled to 100Hz for performance analysis purposes without any information loss.

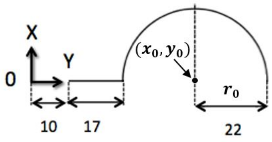

Fig. 2. Reference trajectory (the length measurements are in millimeter)

D. Experimental task and sample description

The task we defined can be accomplished using one or two master interfaces so that it does not favor one of the teleoperation systems in advance. This task consists of cutting a phantom tissue while ensuring a given cutting depth in the vertical direction and a given cutting trajectory in the lateral directions. A blade is vertically fixed to the force sensor and a transparent, soft phantom tissue is laid down on an aluminum foil above another phantom tissue in the slave's workspace. The used phantom tissues for the experiments are created using gelatine.

The participants were asked to manipulate the blade via the teleoperation system to cut the phantom tissue according to the instructions. A straight line followed by a semi-circle was drawn on the tissue and is followed during the cutting process (Fig. 2). The shape fits in a rectangle of $61 \times 22\,mm^2$. The thickness of the phantom tissue is $10\,mm$. The participants were also asked not to cut the aluminum foil while performing the task.

The task is achieved when the shape is all cut out.

The two master interfaces are located on each side of the computer screen that provides the 2D view. The master interface on the left side is used for the unimanual teleoperation system while both master interfaces on the right and left sides are used for the bimanual teleoperation system. Participants were standing in front of the computer screen. Depending on user preference, whether the user's right-hand or the user's left-hand could be used to manipulate the master interface of the unimanual teleoperation system.

Six right-handed volunteers (six males; average age of 24) from the University of Alberta community were recruited as participants, consisting of both undergraduate and graduate students [1]. One subject has prior experience with using 6-DOF input devices.

E. Procedure

A short questionnaire was administered to collect subject information, such as age, hand dominance, and previous experience with 6-DOF haptic devices. At the start of the session, subjects were given a general description of the experimental procedure. Specific instructions for using the master HD^2 interface were then presented, followed by six minutes of practice. Each subject was given one practice trial for each of unimanual and bimanual teleoperation. The practice session started with unimanual teleoperation, followed by a second practice trial for bimanual teleoperation. Then, in the actual recorded experiments, the participants were asked to manipulate one or two interfaces to control the slave manipulator in order to achieve the cutting task. Each participant was given three trials with each teleoperation

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[1] Ethics approval number: Pro00057919

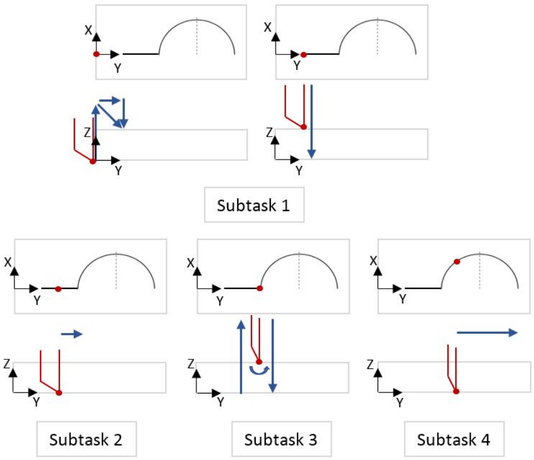

Fig. 3. The cutting procedure. The blue arrow indicates the motion of the cutting tool tip (dark red point) in the phantom tissue (grey rectangle).

system and were asked to carry out the task as accurately as possible. The sequence of trials was randomized. The entire experimental session lasted approximately an hour. For each trial, the time and the trajectories of the slave robot end-effector were recorded. Twelve trials for unimanual teleoperation system and thirteen trials for bimanual teleoperation system were usable for the statistical analysis. The balanced design produced unbalanced data since for some trials the task could not be completed by the participant because of software issues.

In order to describe the system performance, each participant was asked to complete a questionnaire. Participants were asked to evaluate the two proposed teleoperation systems in terms of accuracy and ease of operation. A grade on a scale of 1 (bad) to 5 (good) was given by each participant for the maneuverability of and the confidence in using the system, the ease of learning, the sense of environment and finally for the fatigue.

F. Task sequence and segmentation

The tip of the blade was considered to be the slave robot's end-effector. The depth of the tip at its initial position is the desired depth to be maintained during cutting. The task consisted of the following four operations (Fig. 3):

1) Reach with the slave's end-effector the beginning point of the straight line without cutting the tissue. Then, reach the desired cutting depth. There are multiple possible paths to achieve this operation.
2) Cut the tissue by following the straight line while maintaining the desired depth.
3) Take the blade off the tissue and rotate the blade to align it with the initial part of the semi-circle. Then, reach the desired cutting depth.
4) Cut the tissue by following the semi-circle while maintaining the desired depth.

Subtasks 1 and 3 served to position the tool and insert it to the desired depth before cutting. The data was segmented based on the tool depth. When the slope of the tool depth plot as a function of the time is large, it was considered as entering subtasks 1 and 3. When the slope of the tool depth plot is small, it was considered as entering subtasks 2 and 4. The segmentation for the four subtasks is shown in Fig. 4.

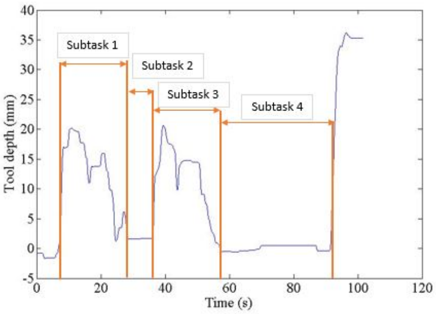

Fig. 4. Sample tool trajectory in the z-direction and its segmentation into the four subtasks

G. Performance measures

The end-effector positions and the task completion time of each trial were recorded and processed to compute the following measures:

- Trajectory tracking. The trajectory tracking analysis was performed for the subtasks 2 and 4. The Dynamic Time Warping (DTW) algorithm was implemented in order to determine the similarity between the reference trajectory and the trajectory recorded for each trial. DTW constructs a global cost matrix with a proper cost function by aligning the two temporal series [18]. A minimum path through the matrix is then determined. The cost of this minimum path corresponds to a match between the two series. The DTW algorithm was implemented for each axis separately. The cost function is defined in Table I for each subtask. The end-effector position signals for each trial were filtered with a Butterworth low-pass filter of order 2 and a cut-off frequency of 1 Hz.
- Completion time. Completion time is the time that it takes the participant to achieve the task.
  A stopwatch was used to record the task completion time. However, for greater accuracy, only the time derived from recorded data via Matlab is used in the analysis.

In order to compare data based on different time scales, the participant datasets were normalized against time.

IV. EXPERIMENTAL RESULTS

The following section compares the results based on the two performance measures mentioned above and introduces the results of the evaluation for the two teleoperation systems. Further trials can be completed for greater confidence in statistics generated from the experimental data.

A. Trajectory tracking

For this error metric, Cartesian coordinates of the reference trajectory and the actual slave robot's end-effector trajectory

Subtask 2 (straight line): x-axis	Subtask 2 (straight line): z-axis	Subtask 4 (semi circle): xy-plane	Subtask 4 (semi circle): z-axis
$e = (x_{tool} - x_{reference})^2$	$e = (z_{tool} - z_{reference})^2$	$e = (\sqrt{(x_{tool} - x_0)^2 - (y_{tool} - y_0)^2} - r_0)^2$	$e = (z_{tool} - z_{reference})^2$

TABLE I

COST FUNCTIONS USED IN THE DTW ALGORITHM FOR EACH SUBTASK ($x_{reference} = z_{reference} = 0$)

	Subtask 2 : x-axis		Subtask 2 : z-axis		Subtask 4 : xy-plane		Subtask 4 : z-axis	
	Median	Std Dev	Median	Std Dev	Median	Std Dev	Median	Std Dev
Unimanual	22.84	19.49	25.83	20.86	117.63	94.20	16.20	10.54
Bimanual	24.16	19.96	7.54	7.08	49.12	38.70	15.49	17.54
Median test p-values	$p = 0.8579$		$p = 0.5458$		**p=0.0165**		$p = 0.8505$	

TABLE II

STATISTICAL SIGNIFICANCE OF TRAJECTORY TRACKING ACCURACY FOR THE UNIMANUAL AND BIMANUAL TELEOPERATION SYSTEMS

were compared using the DTW algorithm. The effect of separation of the DOFs on accuracy is investigated using the non-parametric Median Test with p-value less than 0.05 declared as a statistically significant difference. Obvious outliers were removed from datasets. Regarding the DTW global cost on each axis (i.e., the match between the reference trajectory and the trajectory recorded for each trial), the difference between the teleoperation systems is not statistically significant ($p > 0.05$) except for the accuracy in cutting along the semi-circle on the xy-plane ($p = 0.0165$) as shown in Table II. A t-test does not show any significant difference between the two teleoperation systems in completion time for subtask 4 ($p = 0.1477$). On average, unimanual teleoperation mode ($Mean = 43.34s$; $StdDev = 12.30s$) results in higher completion time than bimanual teleoperation mode ($Mean = 35.18s$; $StdDev = 14.87s$) for subtask 4. Following the semi-circle pattern requires to move the blade in the xy-plane and to rotate the blade about the z-axis while maintaining the desired depth. This result suggests that controlling the tool depth with another hand separate from the one that controls the simultaneous translations and rotations required for tracking the semi-circle leads to better accuracy. This makes sense because the difficulty for the user is when the path involves several complex simultaneous translations and orientations. Using two master interfaces allows to decrease the number of DOFs controlled by the same hand so that the complexity of the task is reduced overall and better accuracy is achieved.

B. Completion time

Completion time gives the time needed by each participant to perform the entire cutting task with either of the both teleoperation systems. This metric is essential since an operator should be able to perform a task within a reasonable time. No specific instruction was provided to the participants regarding the completion time. Nevertheless, participants were aware that the time was recorded for each trial. Multiple linear regression was used and prevalence variables were obtained with 95% confidence interval. Standard least-squares method was used for multiple regression analysis. 76% of the total variance in the task completion time is accounted for by the variables in the linear regression model ($R^2 = 0.7644$). Moreover, the residuals of the model are random and Normally distributed around zero. The p-values associated with the variables selected for multiple regression are introduced in Table III. The multiple regression confirms that the separation of the DOFs (teleoperation mode) has a significant effect on the completion time ($p = 0.0165$). On average, unimanual teleoperation mode ($Mean = 104.30s$; $StdDev = 21.13s$) results in higher completion time than bimanual teleoperation mode ($Mean = 84.43s$; $StdDev = 26.05s$) for the entire task. Following the reference trajectory needs simultaneous rotations and translations. For the unimanual teleoperation system, these motions are coupled to the tool depth motion whereas for the bimanual teleoperation system the tool depth motion is controlled through the second master interface. The DOF decomposition allows the user to translate and rotate the blade without altering the tool depth and prevents the user from having to continuously adjust the tool depth, which is time-consuming. Thus, from the time perspective as well, bimanual is superior to unimanual teleoperation for the task considered.

Source	F Ratio	Prob > F
Mode (unimanual or bimanual)	7.9845	**0.0165**
Order of trials (1-2-3)	2.8262	0.1022
Participant (from 1 to 6)	3.1213	0.0605
Participant*Mode	2911.2524	0.1372
Order of trials*Mode	0.5729	0.5799

TABLE III

EFFECT SUMMARY FROM THE MULTIPLE REGRESSION ANALYSIS

C. User evaluation

Participants were asked to evaluate both systems they used during the experiments. The average of the grades given by each participant is shown in Fig. 5. The use of two master interfaces to control complementary DOFs offers the best score in the maneuverability to accomplish the task, ease of learning and sense of environment. Users are also more confident and less tired when they use the bimanual telepeoration system than the unimanual teleoperation system. The maneuverability is strongly influenced by the DOF decomposition; the user is able to consider separately different motions required in the achievement of the task, which

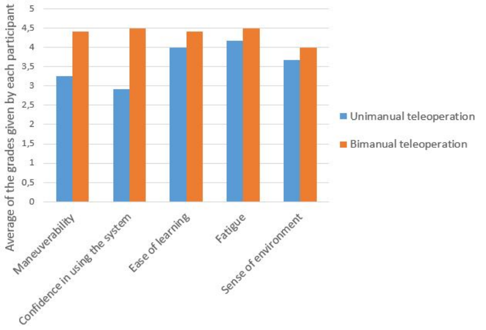

Fig. 5. Histogram showing the evaluation of both unimanual and bimanual teleoperation systems by the participants. Grades are given on a range from 0 to 5 (5 is the best grade).

makes the control of the tool motion easier. Furthermore, no discomfort was noticed due to the DOF decomposition which could possibly increase the cognitive load of the task [19]. The participants were able to analyse the visual information, infer the appropriate motion and coordinate their two hands to perform the desired motion.

V. CONCLUSIONS

From the experimental results presented in the paper, we can conclude that the use of a bimanual teleoperation system with complementary DOFs decreases the completion time without negatively affecting the precision of the system for a task which involves following a pattern while maintaining a desired depth. In bimanual teleoperation, the completion time average is reduced by 19% compared to unimanual teleoperation. Users also reported being more comfortable with the bimanual teleoperation system in performing the cutting task. We showed that in certain situations, splitting the number of DOFs between a user's two hands leads to better performance. However, it is necessary to understand which strategies are adopted by the users to understand why the DOF decomposition introduced in this paper decreases the completion time and if another DOF decomposition would obtain the same results. The main point is that the DOF decomposition prevents a motion along an axis with the first master interface from affecting another motion along another axis controlled by a second master interface. This allows the user to better execute separate but simultaneous motions. To generalize this conclusion, other tasks should be studied in the future. For instance, a needle insertion task could be considerated with a similar DOF separation: one master interface could control the lateral position and axial orientation of the needle tip whereas a second master interface would control its insertion depth.

ACKNOWLEDGMENT

This work was supported by the Canada Foundation for Innovation (CFI) under grant LOF 28241, the Alberta Innovation and Advanced Education Ministry under Small Equipment Grant RCP-12-021, a University of Alberta startup grant, the Quanser, Inc., and the Natural Sciences and Engineering Research Council (NSERC) of Canada under grant CRDPJ 411603. An AMOPA Higher Education Scholarship and an Explo'ra Sup Grant were awarded to Maëlle Agbalé for supporting this research. An NSERC USRA Scholarship was awarded to Renz Ocampo.

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