Intuitive adaptive orientation control of assistive robots for people living with upper limb disabilities

Dinh-Son Vu*[1], Ulysse Côté Allard*[2], Clément Gosselin[1,3],
François Routhier[3,4], Benoit Gosselin[2,3], Alexandre Campeau-Lecours[1,3]

***Abstract*— Robotic assistive devices enhance the autonomy of individuals living with physical disabilities in their day-to-day life. Although the first priority for such devices is safety, they must also be intuitive and efficient from an engineering point of view in order to be adopted by a broad range of users. This is especially true for assistive robotic arms, as they are used for the complex control tasks of daily living. One challenge in the control of such assistive robots is the management of the end-effector orientation which is not always intuitive for the human operator, especially for neophytes.**

This paper presents a novel orientation control algorithm designed for robotic arms in the context of human-robot interaction. This work aims at making the control of the robot's orientation easier and more intuitive for the user, in particular, individuals living with upper limb disabilities. The performance and intuitiveness of the proposed orientation control algorithm is assessed through two experiments with 25 able-bodied subjects and shown to significantly improve on both aspects.

I. Introduction

The human body is inherently limited by its physical attributes. Robotics is seen as a key solution to circumvent such limitations. Physical human-robot interaction is the area of robotics that strives to achieve this goal [1, 2]. In particular, the field of rehabilitation robotics aims at improving the autonomy of individuals living with functional impairments [3]. This area of research includes the development of innovative robotic systems able to assist end-users in their everyday tasks. For instance, assistive robotic arms is a field of rehabilitation robotics that aspires to elevate the capabilities and skills of individuals living with upper limb disabilities [4].

The JACO arm produced by Kinova [4] is a six-degree-of-freedom (6 DOF) robotic arm controlled with the wheelchair drive control (for instance a joystick). In the context of assistive robotics, JACO aims to assist individuals living with upper limb disabilities to perform activities of the daily living (e.g. grabbing objects, eating, drinking). Initial studies [5, 6] showed that the robot could be controlled precisely to perform such tasks. The performance and intuitive control of such devices is important to accomplish these complex tasks on a day-to-day basis. However, controlling such a complex assistive device is not straightforward, especially for people living with physical limitations. In telerobotics [7, 8], the user interface, the mapping of the commands to control the robot, and the user perspective of the robot movement may affect the final task accomplishment. In the instances where the degree of impairment is severe, the need for intuitiveness and ease-of-use increases due to the fact that every action requires more effort and is more time consuming. Different approaches have thus been proposed in the literature to improve the performance of assistive robots. For instance, intelligent control algorithms have been proposed [4, 9] to let the operator manage higher level tasks while letting the robot manage lower level ones, thus leading to a reduction of the required time and effort to perform a task. Advanced user interfaces and their respective mapping commands have also been proposed [10, 11, 12] to enhance the user performance and extend the robot's usage to a wider range of individuals.

Nevertheless, in a private survey made by Kinova, the control of the end-effector (hand) orientation has been reported as not intuitive and difficult to understand and thus, poorly suited for human-robot interaction. As it is the case with the majority of cooperative robots, JACO's orientation control was derived from industrial applications. This orientation system is based on velocity commands that rotate the hand of the robot around the tool frame (cf. Figure 1).

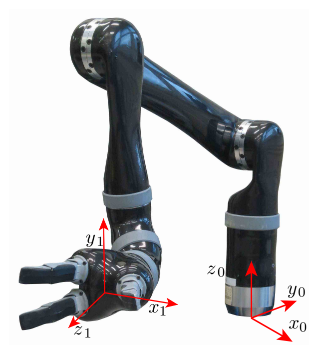


Fig. 1: Assistive robot JACO with the definition of the the reference frame $[x_0, y_0, z_0]$ and the mobile tool frame $[x_1, y_1, z_1]$.

This paper presents a novel orientation control algorithm based on the definition of a new adaptive reference frame. This reference frame automatically adapts to the robot's position and orientation, which allows the robotic arm to behave in a predictable way for the user, leading to a system

[1]Department of Mechanical Engineering, [2]Department of Computer and Electrical Engineering, Université Laval, 1065 Avenue de la médecine, Québec, QC, G1V 0A6, Canada
[3]Department of Rehabilitation, [4]Center for interdisciplinary research in rehabilitation and social integration, Centre intégré de santé et de services sociaux, Institut de réadaptation en déficience physique de Québec, 525 Hamel est, Québec, QC, G1M 2S8, Canada
Contact author email: alexandre.campeau-lecours@gmc.ulaval.ca
*These authors contributed equally to this work

that is more intuitive than existing ones. The objective of the proposed control scheme is to enable the end-user to complete tasks more efficiently and with less effort. The paper first presents the existing and the proposed orientation control. Two experiments are then presented in order to assess the algorithm's performance. Finally, a qualitative assessment of the system's performance and intuitiveness is presented.

II. Orientation Control

Figure 1 presents the serial robot JACO and the position of the fixed reference frame defined by the axes $[x_0, y_0, z_0]$ with the z_0 axis pointing upward. The mobile tool frame is defined by the axes $[x_1, y_1, z_1]$ with the z_1 axis pointing out from the robot's palm.

A. *Fixed-frame rotation*

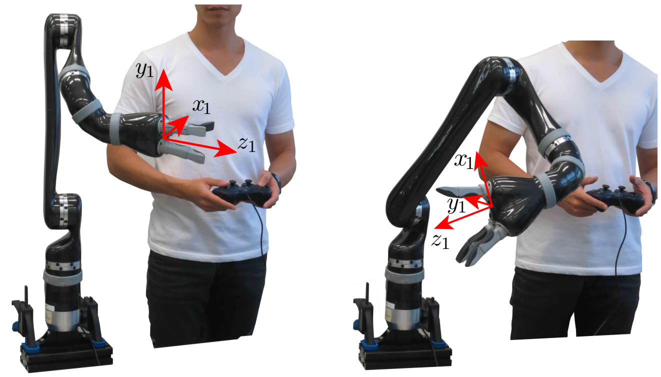
One common method to define the robot's end-effector rotation is based on Euler angles. Three successive rotations of angles around predetermined axes defined by the fixed reference frame $[x_0, y_0, z_0]$ determine the final orientation of the effector. This rotation system is often used by industrial robots for pre-programmed trajectories. However, the manual control of the rotations with the Euler angles is highly non-intuitive for the operator as it is not directly defined in the task frame.

B. *Tool-frame rotation*

The tool-frame system corresponding to $[x_1, y_1, z_1]$ in Figure 1 is defined in the task space. For instance, a rotation around the forearm z_1 axis (which is useful in practice) would require a combination of three rotations with the fixed-frame system while it represents only a single direct command around the z_1 axis with the tool-frame system. This classical tool-frame rotation system is used for the manual operation of industrial robots and is also used to control the robotic assistive device JACO. However, while this mode is easier to operate than the fixed-frame rotation system, the tool-frame rotation system still has been reported as not intuitive and difficult to understand in a human-robot collaboration context.

As an example, Figure 2 shows two possible configurations of the robot arm. When the robot is in its default position (cf. Figure 2a), the robot's motions are intuitive since the user can identify the movement of the robot as his/her own arm. However, when the robot's wrist is not aligned with the arm of the user (see Figure 2b), the orientation control of the hand becomes less intuitive since the tool-frame rotation system moves relative to the end-effector. Several trial-and-error manoeuvres are then necessary in order to find the required input to achieve a given motion which is time consuming and requires much effort. The orientation control becomes even less intuitive when the robot's hand is purely pointing downward or upward due to the loss of the user's internal representation of the mobile tool frame.

Figure 3 shows one common issue with the classical tool frame rotation system. Regardless of the control interface,

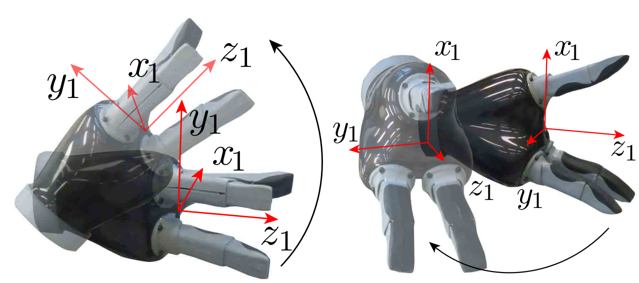


(a) Intuitive configuration of the robot aligned with the right arm of the user.

(b) Non-intuitive configuration of the robot with the palm facing outward.

Fig. 2: Different scenarios for the robot configuration.

the user can control the orientation of the arm through rotations about the axes x_1, y_1 and z_1. In Figure 3a, when the user sends a positive command to rotate around axis x_1 (for instance pushing the joystick forward), the hand rotates upward around a horizontal axis. In Figure 3b, the hand is at the same position and orientation as in case of the Figure 3a, except that the hand has rotated 90 degrees around axis z_1. By using the same command (i.e. pushing the joystick forward), the user would expect the hand to rotate upward as in case of the Figure 3a. However, because the rotation is around mobile axis x_1, which has shifted compared to case of the Figure 3a, the same command makes the arm rotate to finally face right. This behaviour is counter-intuitive, especially when the arm is in a non-intuitive configurations (see Figure 2b). This ambiguity in the manual control of the orientation can be solved with the control algorithm proposed in this paper.



(a) (b)

Fig. 3: Different scenarios showing how the tool-frame system can lead to drastically different behaviors for the same control inputs depending on the end-effector's orientation.

C. *Adaptive tool-frame rotation*

The proposed orientation control method solves the aforementioned problem by defining of a new rotation frame $[x_2, y_2, z_2]$, as shown in Figure 4. The rotation around the z_1 axis (pointing out of the palm) orient the end-effector

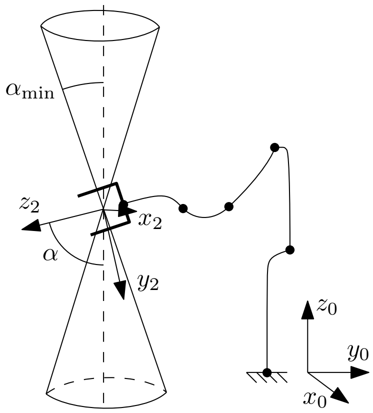


Fig. 4: Presentation of the anti-singularity cones defined to prevent the miscalculation of the vector $\mathbf{e}_{x2}$. The direction of the x_2 axis is parallel to the horizontal plane whereas the y_2 axis is inverted for a more intuitive control with the left/right joystick.

to rapidly adapt to the shape of the object (e.g. grasping a rectangular object by its width instead of its length). Additionally, from an anthropomorphic point-of-view, the supination/pronation of the human forearm is performed long the z_1 axis.

The unit vector $\mathbf{e}_{x2}$ corresponding to direction of the x_2 axis is obtained using

$$\mathbf{e}_{x2} = \frac{\mathbf{e}_{z0} \times \mathbf{e}_{z2}}{||\mathbf{e}_{z0} \times \mathbf{e}_{z2}||}. \tag{1}$$

where $\mathbf{e}_{z0}$ and $\mathbf{e}_{z2}$ are the unit vectors corresponding to their respective axes. The geometrical interpretation of Eq. (1) shows that the x_2 axis is perpendicular to the fixed axis z_0, that is pointing upward, and perpendicular to the mobile axis z_2, that is pointing out of the robot's palm. Therefore, the x_2 axis is always defined in the horizontal plane while remaining orthogonal to the axis pointing out of the robot's hand (cf. Figure 4). In comparison, the direction of the x_1 axis of the classical tool-frame system changes depending of the other rotations around the axes y_1 and z_1, and can even point upward as shown in Figure 3b. Consequently, the ambiguity in the tool-frame orientation control depicted in Figure 3 is solved using the proposed method since the x_2 axis is always defined in the horizontal plane.

Unfortunately, using the adaptive tool-frame rotation, vector $\mathbf{e}_{x2}$ is undefined when the axes z_0 and z_2 are collinear, namely when the hand of the robot is pointing upward or downward. In order to obtain an expression of $\mathbf{e}_{x2}$ at these singular orientations, the angle α between the vectors $\mathbf{e}_{z0}$ and $\mathbf{e}_{z2}$ is calculated as follows

$$\alpha = \cos^{-1}\left(\mathbf{e}_{z0} \cdot \mathbf{e}_{z2}\right). \tag{2}$$

If the angle α is below the threshold $\alpha_{\min}$, then vector $\mathbf{e}_{x2}$ is equal to vector $\mathbf{e}_{x0}$, which defines the direction of the axis x_0, namely

$$\text{if } \alpha < \alpha_{\min} \text{ then } \mathbf{e}_{x2} = \mathbf{e}_{x0}. \tag{3}$$

$\alpha_{\min}$ describes two symmetrical and vertical cones at the robot's hand as shown in Figure 4. The modification of the frame due to the singular configuration occurs when the user stops in the anti-singularity cone. If he/she maintains the movement through the cone, the switch does not occur.

Finally, the direction of the vector $\mathbf{e}_{y2}$ completes the frame of reference of the new orientation method, namely

$$\mathbf{e}_{y2} = -\mathbf{e}_{z2} \times \mathbf{e}_{x2}. \tag{4}$$

It can be noticed that the calculation of the vector $\mathbf{e}_{y2}$ contains a minus sign that reverses the direction of the second axis compared to a regular orthonormal frame. This operation allows an orientation to the right of the robot with an input to the right on the controller pad, shown in Figure 5, and an orientation to the left with an input to the left, which is considered to be more intuitive.

D. Orientation Control Mapping

Regardless of the interface used to control the assistive robotic arm (e.g. joystick, Sip-and-Puff system, buttons, IMU, EMG), the lack of intuitivity of the actual orientation control systems remains the same. In this paper, the control interface used is shown in Figure 5.

Arbitrary rotation of the end-effector requires at least three degrees of freedom, thereby the upward/downward movement of the left joystick, the lateral movement of the left joystick and the upward/downward movement of the right joystick are used in order to map the orientation of the effector. Positive rotation refers to a counter clockwise rotation according to the right-hand rule.

The directional pad is used to map the frontward/backward and the left/right translations in the Cartesian space of the end-effector whereas two triggers on top of the controller are used in order to map the upward/downward translational movement.

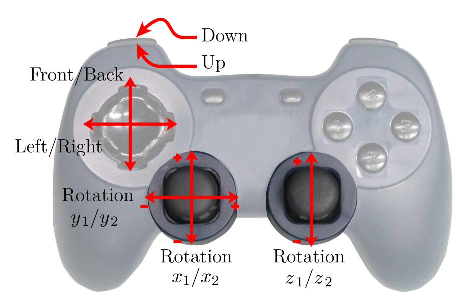


Fig. 5: Control map of the robot's movement with the controller pad.

The orientation control using the classical mobile tool frame $[x_1, y_1, z_1]$ —hereafter referred to mode A— is as follows:

- Upward or downward movement of the left joystick rotates the effector around the x_1 axis.
- Left or right movement of the left joystick rotates the effector around the y_1 axis.
- Upward-Downward movement of the right joystick rotates the effector around the z_1 axis.

(a) Position 1
Joystick input: Up
Mode A: face up
Mode B: face down

(b) Position 2
Joystick input: Up
Mode A: face front
Mode B: face down

(c) Position 3
Joystick input: Right
Mode A: face left
Mode B: face right

(d) Position 4
Joystick input: Right
Mode A: face front
Mode B: face right

(e) Position 5
Joystick input: Upward
Mode A: face down
Mode B: face down

Fig. 6: Position of the robot for the first experiment, input of the joystick and the response for the corresponding mode.

The control of the orientation with the new frame of reference $[x_2, y_2, z_2]$ —hereafter referred to as mode B— with the controller pad is defined as follows:

- Upward or downward movement of the left joystick rotates the effector around the x_2 axis.
- Left or right movement of the left joystick rotates the effector around the y_2 axis.
- Upward-Downward movement of the right joystick rotates the effector around the z_2 axis.

An important advantage of the proposed adaptive tool-frame rotation system is that the control can be translated into intuitive instructions rather than on rotations around the axes of a given frame. This is especially important because the users are typically not experts in robotics. The orientation control can thus be simplified in the following terms:

- Upward or downward movement of the left joystick rotates the effector downward or upward.
- Left or right movement of the left joystick rotates the effector to the left or to the right.
- Upward-Downward movement of the right joystick rotates the effector around the z_2 axis, counter-clockwise or clockwise.

III. Experimental validation

In order to evaluate the intuitiveness and the performance together of the proposed orientation control system two experiments were conducted. The first experiment assesses how easy it is to predict the behaviour of mode A and mode B while the second experiment evaluates both modes in a complex control task using the joystick. 25 participants aged between 22 and 41 participated in the experiments. Each participant started with the mode that the previous participant finished with. The first mode use by the first participant was selected randomly. Instructions about how to operate the corresponding modes were given to the users while they were getting accustomed to the controller pad for five minutes.

A. Experiment 1: understanding the orientation system

The first experiment aims to evaluate if participants understand the rotation systems well while using the joystick with the mode A (orientation with the tool frame $[x_1, y_1, z_1]$) and the mode B (orientation with the proposed adaptive tool frame $[x_2, y_2, z_2]$). Then, the robot was set to five positions in succession as shown in Figure 6. For each position, the participant was asked which direction the robot's hand would face if given a specific command.

The user was evaluated on the time to give an answer and on the validity of his/her answers. One point was granted if the given orientation was correct, half a point if the opposite direction was given (i.e. correct rotation axis, but wrong direction) and no point otherwise. Therefore, the maximum number of errors (incorrect answers) is five.

Figure 7 shows the results of the experiment. For each participant, the number of errors is depicted in the vertical coordinate whereas the average time taken to answer is depicted in the horizontal coordinate. When mode A is used (classical tool frame), the average number of errors is 2.7 with an average time of 7.5 sec to answer. When mode B is used (proposed tool frame), the average number of errors is 0.3 and the average time to answer is 3.2 sec. The standard deviations with mode A are $\sigma_{\mathrm{time}A1} = 4.55$ sec for the time and $\sigma_{\mathrm{error}A1} = 1$ for the number of errors whereas, with the mode B, the standard deviations are $\sigma_{\mathrm{time}B1} = 1.93$ sec and $\sigma_{\mathrm{error}B1} = 0.49$, which are smaller than with mode A.

Indeed, subjects dealing with mode A displayed two kinds of behaviours: in the first case, users tried to truly understand the frame of reference and its corresponding behaviour for each position resulting in more accurate answers with more time to answer. In the second case, participants tried to give their answers quickly based on their intuition. The first case generally slowed the response time, while the second case tended to reduce the accuracy.

The average completion time using mode B was statistically significantly reduced by an average of 57% compared to mode A ($p = 2.48\mathrm{e}^{-5} < 0.05$, Wilcoxon signed-rank one-tailed test). The answers' accuracy were also statistically significantly improved by 87% ($p = 8.64\mathrm{e}^{-6} < 0.05$). Using the proposed control system, participants were thus able to give more precise answers much faster.

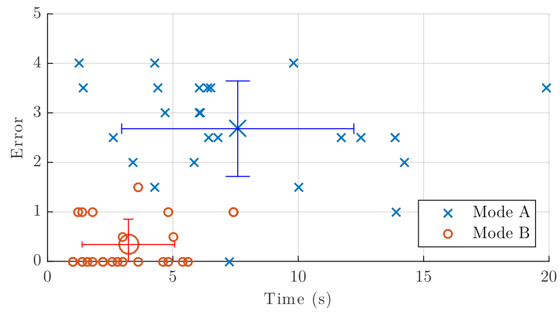


Fig. 7: Results of the first experiment with the number of errors and the average time taken to answer each position.

B. Experiment 2: Performing an orientation task

After performing the first experiment, the subjects were asked to perform the second experiment. Many daily tasks require to control the orientation of the assistive robot's hand. Such tasks may include picking up objects (a glass of water, a pencil on a table, remote control on the ground), pushing a button (elevator), paying with a card, etc. The task to be performed with the robot in this experiment was defined based on the manipulation of a card in order to assess the performances of the rotation algorithm.

In order to simplify the trajectory and to focus on the orientation control, the card was already placed in the robot's palm so that the grasping task was not taken into consideration. The trajectory of the hand began at the initial position of the robot shown in Figure 8. The user then had to place the card as to overlay the three rectangles in the image. Each participant had to complete the following trajectory: (1)→(2)→(3)→(1).

The required orientation of the card at each position was shown on a sheet of A4 paper (cf. Figure 8). The position

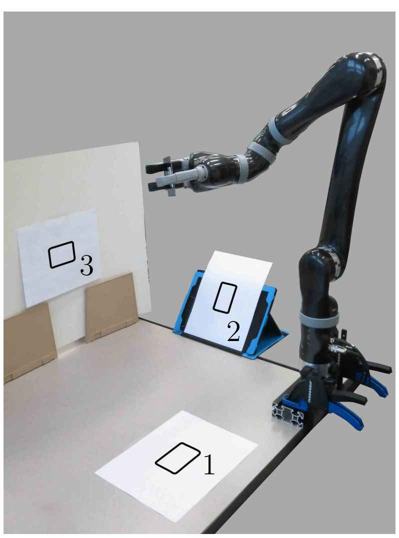


Fig. 8: Set up of the markers for the trajectories of the second experiment. The robot holds a card which has to face each of the surfaces indicated with one black rectangle.

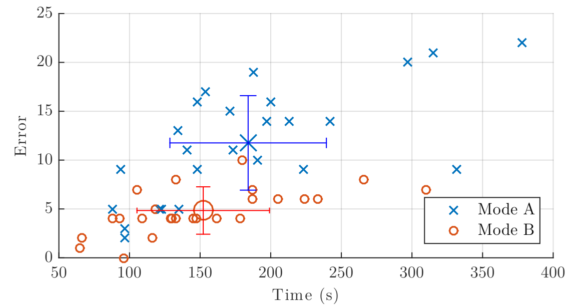


Fig. 9: Results of the second experiment with the number of errors while orienting the robot and the time taken to complete the task.

of the card had to be within the paper boundaries and its orientation had to be parallel to the paper. To avoid the collision between the fingers and the surfaces, a distance of 3 cm to 5 cm between the tip of the fingers and the paper was sufficient to validate one marker. The participants were first evaluated based on the time to complete the task. Error points were also compiled when the user performed a wrong joystick command to perform a given rotation. For example, rotating the robot hand to the right plane whereas the target was on the horizontal plane led to increase the error counter. For this task, errors made by the participant while using the robot in translation control were omitted.

Figure 9 shows the results of this experiment. The participants that had begun the first experiment with mode A also began with mode A for the second experiment and vice versa. The task completion time is shown in the horizontal coordinate whereas the number of errors is shown in the vertical coordinate. The average time taken in order to perform the trajectories with mode A is 184 sec with an average number of error of 11.7 errors while mode B shows a better performance with an average completion time of 152 sec and an average of 4.8 errors. The standard deviations with mode A are $\sigma_{\text{time}A2} = 78.1$ sec for the time and $\sigma_{\text{error}A2} = 5.74$ for the number of errors whereas, with the mode B, the standard deviations are $\sigma_{\text{time}B2} = 61.41$ sec and $\sigma_{\text{error}B2} = 2.3$, which are smaller than with mode A.

The completion time was significantly statistically reduced by 17$\%$ with mode B compared to mode A ($p = 0.003 < 0.05$). The number of errors was also significantly statistically reduced by 59$\%$ ($p = 1.23e^{-5} < 0.05$). The results of the two experiments corroborate the assessment of the orientation control being more efficient and intuitive with mode B (proposed adaptive orientation control) rather than with mode A (classical tool frame orientation control).

C. Qualitative assessment of the system's intuitiveness

The main purpose of the proposed orientation control system is to enhance the users' experience by enabling them to control the robot with more performance and intuitiveness. Apart from quantitative data obtained in the preceding experiments, an important metric is the participant preference. Following this, the most important rubric must be which system the participants qualitatively preferred. To that effect, at the end of the experiments, participants were asked if they experienced the first mode as more intuitive and efficient than the second mode. In order to eliminate any bias, the question referred to the first mode they used and they did not know if this mode was the classical or the newly proposed mode. The participants could choose one of the following five answers: totally disagree, disagree, they were equal, agree and totally agree. In all but one case, the subjects preferred using the new proposed mode over the classical mode. Additionally, many participants commented that they could easily understand the control of new proposed mode whereas they had to control classical mode mostly through trial and error. Participants instinctively concluded that they could not accurately and efficiently predict the behaviour of the robot under classical mode, even without knowing their quantitative results. These qualitative results corroborate the conclusions from the previous experiments. That is, the orientation control system presented in this paper is more intuitive than the tool-frame rotation system.

IV. Conclusion

In this work a novel, intuitive orientation control algorithm for assistive robotic arms is proposed. The proposed system was implemented on the JACO robot from the company Kinova, but can easily be extended to any other robot. Both of the experiments conducted in this work confirmed that the novel orientation algorithm is significantly more intuitive and efficient to operate. Furthermore, all participants intuitively preferred the proposed orientation control method.

Future work will focus on clinical validation with motor impaired end-users utilizing different control modalities. These tests will be used to assess the algorithm's performance in real life scenarios and to find possible improvements.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Research Chair Program.

References

[1] S. Haddadin and E. Croft. "Physical Human–Robot Interaction". In: *Springer Handbook of Robotics*. Springer, 2016, pp. 1835–1874.

[2] C. Gosselin, B. Mayer-St-Onge, S. Foucault, A. Lecours, V. Duchaine, D. Gao, and R. Menassa. "A Friendly Beast of Burden". In: *IEEE Robotics & Automation Magazine* October (2013), pp. 139–147.

[3] H. F. M. Van der Loos and D. J. Reinkensmeyer. "Rehabilitation and Health Care Robotics". In: *Springer Handbook of Robotics* (2008), pp. 1223–1251.

[4] A. Campeau-Lecours, V. Maheu, S. Lepage, H. Lamontagne, S. Latour, L. Paquet, and N. Hardie. "JACO Assistive Robotic Device: Empowering People With Disabilities Through Innovative Algorithms". In: *Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Annual Conference* October (2016).

[5] F. Routhier and P. S. Archambault. "Usability of a Joystick-Controlled Six Degree-of-Freedom Robotic Manipulator". In: *Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) Annual Conference* 703 (2010), pp. 1–7.

[6] V. Maheu, P. S. Archambault, J. Frappier, and F. Routhier. "Evaluation of the JACO robotic arm: Clinico-economic study for powered wheelchair users with upper-extremity disabilities". In: *IEEE International Conference on Rehabilitation Robotics* (2011), pp. 4–6.

[7] J. Y. C. Chen, E. C. Haas, and M. J. Barnes. "Human performance issues and user interface design for teleoperated robots". In: *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews* 37.6 (2007), pp. 1231–1245.

[8] P. G. de Barros and R. W. Lindeman. *A Survey of User Interfaces for Robot Teleoperation*. Worcester Polytechnic Institute, 2009.

[9] L. V. Herlant, R. M. Holladay, and S. S. Srinivasa. "Assistive Teleoperation of Robot Arms via Automatic Time-Optimal Mode Switching". In: *The Eleventh ACM/IEEE International Conference on Human Robot Interation*. IEEE Press. 2016, pp. 35–42.

[10] C. L. Fall, P. Turgeon, A. Campeau-Lecours, V. Maheu, M. Boukadoum, S. Roy, D. Massicotte, C. Gosselin, and B. Gosselin. "Intuitive wireless control of a robotic arm for people living with an upper body disability". In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS* 418 (2015), pp. 4399–4402.

[11] D. Bassily, C. Georgoulas, J. Güttler, T. Linner, T. Bock, and T. U. München. "Intuitive and adaptive robotic arm manipulation using the leap motion controller". In: *Isr Robotik* (2014), pp. 78–84.

[12] U. Côté Allard, F. Nougarou, C. L. Fall, P. Giguere, C. Gosselin, F. Laviolette, and B. Gosselin. "A Convolutional Neural Network for Robotic Arm Guidance Using Semg Based Frequency-Features". In: *IEEE/RSJ International Conference on Intelligent Robots and Systems* (2016).