An Approach for Online User Customization of Shared Autonomy for Intelligent Assistive Devices

Siddarth Jain and Brenna Argall

I. Introduction

Assistive devices such as powered wheelchairs, assistive robotic arms, extremity prostheses and other aids can promote the functional independence of individuals with disabilities. However, as the complexity of the assistive device increases it becomes challenging to operate with the available control interfaces like 2- or 3-axis joysticks, and even more challenging with the limited interfaces like a sip-and-puff or a head array that are available to individuals with severe motor impairments. For example, the teleoperation of assistive robotic arms involves controlling more than 2 or 3 degrees of freedom, which requires the user to select and switch between several control modes, and thus the control can even become tedious and cognitively burdensome.

The introduction of robotics intelligence to assistive devices aims to offload some of the control burden from the user. In shared autonomy systems the user input and robot autonomy commands are combined to control the intelligent assistive device. An important consideration is *how to modulate the balance between human control and autonomy control such that it is acceptable to the human and at the same time is efficient for task executions*.

Control can be shared in a predefined manner using a fixed autonomy level, however this may fail to perform or generalize in different scenarios or tasks. Assistance in control sharing is often estimated using a predefined arbitration function that is based, for example, on the robot's confidence in its prediction of the user's intent for performing a task. Although such predefined arbitration functions can make the robotic assistance contextual, they may not generalize across users as the amount of assistance required or desired is unique to each user—based on their personal preferences and physical abilities. Likewise automated modulation schemes for control sharing (e.g. based on task-related performance metrics) may not be acceptable for the same reason.

Our target is to make the autonomy in intelligent assistive devices adjustable, so that it fits the user's preferences and unique physical abilities. To this end, we propose the customization of shared autonomy in assistive intelligent devices by the end users themselves in an online manner. We *empower* the user to dictate the amount of shared autonomy by using a *customization interface*, which allows for the online adjustment in the autonomy amount by the users themselves. We *furthermore* aim to evaluate different schemes for online customization of the shared autonomy by the end users. We also propose to evaluate multiple interface design options, and special consideration is given on the simplicity of each interface design.

Siddarth Jain and Brenna Argall are both jointly affiliated with Northwestern University, Evanston, IL 60208, USA and the Rehabilitation Institute of Chicago, Chicago, IL 60611 sidd@u.northwestern.edu, brenna.argall@northwestern.edu

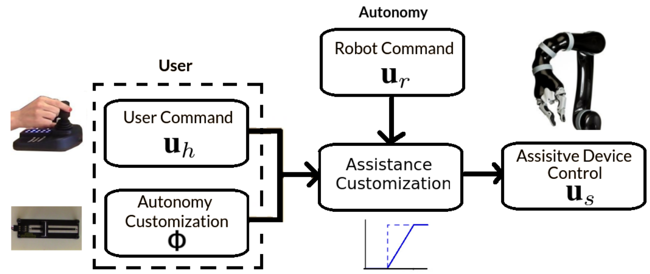

Fig. 1. Autonomy customization by end-users for assistive devices.

In this paper, we describe the design of the proposed *customization interfaces*, discuss different schemes for the online customization of the shared autonomy, present a shared autonomy framework for online customization of assistance and layout our plan to test the effectiveness of the interfaces and each scheme in terms of generalizability and satisfaction across users and tasks.

The larger goal of this work is to investigate following research questions:

Q1 How *effective and acceptable* are the customization interfaces at manipulating the autonomy level in an online fashion?

Q2 Which interface designs can *generalize* to user preferences and abilities?

Q3 Should robotic assistance be based on an *arbitration function* wherein a prediction confidence regulates the amount of assistance? Or, should the user *directly dictate* the exact amount of shared autonomy using the customization interface?

Q4 How should the user input provided through the customization interface *modify* the arbitration function to achieve the optimal assistance?

II. Background

Within the field of assistive robotics, shared autonomy leverages robotics autonomy to make the control of assistive devices easier while keeping the human user in the loop. Many prior works address shared autonomy by having the user select a higher-level goal and the robotics autonomy is responsible for generating lower-level control to assist in achieving that goal [1], [2]. In some methods the robot always has full control of the motion [2] and in others the robot takes control depending on proximity to the goal [3]. Some works achieve control sharing by incorporating partitioning schemes. For example, in [4] the robot assumes full control of the orientation while the user is responsible for the translational motion. Recently, policy blending methods that combine the user controls and the autonomy commands are gaining more interest [5].

Many policy bending approaches can be thought of as an arbitration between the user policy and the robot policy. There exist works that study the nature of the arbitration. You *et al.* [6] found aggressive assistance is better and users prefer fully autonomous control to accomplish complex motions. A study by Kim *et al.* [7] by contrast concludes that users prefer manual control for manipulation tasks that involve grasping. Dragan *et al.* [8] study fixed arbitration functions and find that aggressive assistance is preferable on hard tasks, but on easier tasks there is no consensus among users about the nature of the arbitration behavior. Their work also suggests that different users develop different strategies for executing tasks, indicating that the user's preference changes based on scenarios and task difficulty.

These contradictory findings indicate that existing approaches for shared autonomy do not guarantee acceptance across users and moreover may fail to generalize in different scenarios or tasks. This motivates our idea to hand over the shared autonomy customization to the end users themselves in order to bring about higher user satisfaction and adoption of robotics autonomy in intelligent assistive devices. Our approach allows the users to adapt the assistive system according to their own preferences and abilities—and thus should cater to user satisfaction along with providing important insights for further research in this direction.

III. Proposed Customization Interfaces

We target to empower end users to customize the shared autonomy using a customization interface. It is important to consider the interface design to accommodate different users' abilities. Moreover, the choice of interface may also be affected by the customization scheme in use.

We interviewed and consulted with an Occupational Therapist at the Rehabilitation Institute of Chicago, with a speciality in assistive technology, and an end-user (quadriplegic) to inform the design options for the customization interfaces. Based on these interactions we established four interface designs. Special consideration is given on the simplicity of each design—with the aim for it to be easily operable by people with limited arm and hand function.

The interface options consist of a knob, a slider and a two-button and a single button interface (Figure 2, top). Potentiometers and soft push buttons are used as the primary components to design the interfaces. The Arduino UNO is used for interfacing and the acquisition of signals, along with the ROS (Robot Operating System) serial library to publish the data from the interface to the intelligent assistive device. At any time instant, the interface issues a customization

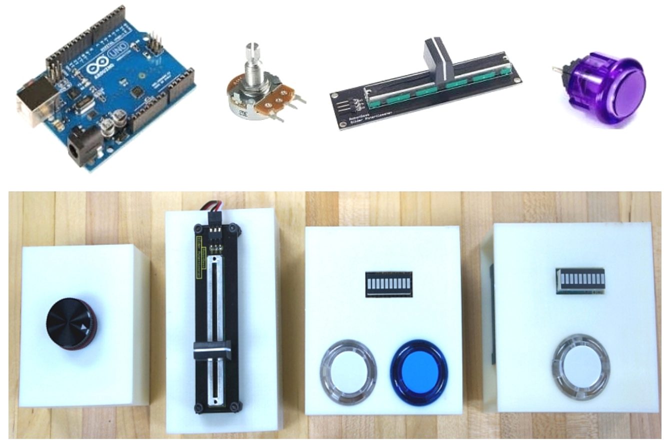

Fig. 2. Top: Interface design components (Arduino UNO, standard potentiometer, slider potentiometer and arcade push button). Bottom: Interface prototypes.

signal $\phi \in [0,1]$, which is used to dictate the shared autonomy level for the assistive device using a given customization scheme (discussed in the next section). The user can change the customization signal ϕ in an online fashion using the interface, which in turn adjusts the autonomy level.

- **Knob interface**: It allows a smooth turning movement and requires some function of the thumb and the fingers for its operation. ϕ increases with the clockwise turn.
- **Slider interface**: It allows smooth lateral movement and does not require movement in the thumb or use of the fingers. ϕ increases as slider moves from bottom to top.
- **Button interfaces**: They allow light press operation and does not require thumb or finger function. In the two-button interface, the left button increases ϕ and the right button decreases it. The single button interface increases ϕ with single press and decreases it with double press within a timed interval.

The interfaces are capable of providing a tailored amount of feedback to the user based on an estimate of the current autonomy level of the system. The knob and slider interface provide feedback of the autonomy level to the user based on the position of the knob dial or the slider respectively. The button interfaces are equipped with an LED bar display to provide the feedback information. The prototype design of the interfaces are given in Figure 2, bottom.

IV. Research Plan

We consider the case of an assistive robotic arm (MICO,[1] Kinova Robotics, Canada) as the intelligent assistive device (Figure 3), and implement a control blending approach to describe and evaluate the customization interfaces, as well as the different schemes for how to adjust the shared autonomy.

Fig. 3. MICO assistive robot and 3-axis joystick (Kinova).

A. Shared Autonomy Framework

At any instant, we blend the human user's control input $\mathbf{u}_h$ and the autonomy control $\mathbf{u}_r$ to calculate the control command $\mathbf{u}_s$ for the assistive system,

$$\mathbf{u}_s = \mathbf{u}_h(1 - \lambda) + \mathbf{u}_r \cdot \lambda \tag{1}$$

where $\lambda \epsilon$ [0,1] is a blending factor that dictates how much control lies with the human versus the autonomy. The determination of λ lies within the customization scheme used for the shared autonomy.

The user commands $\mathbf{u}_h$ are generated using the control interface (a 3-axis joystick) of the assistive robotic arm (Figure 3). User control and autonomy commands operate in the same space (for example, the velocity of the end-effector in $\mathbb{R}^6$). However, at any instant $\mathbf{u}_h$ has either a translational control component or a orientation control component for the end-effector of the robot (and the remainder of the control dimensions are zero)—a common method which requires the user to switch between control modes. Control signals for the autonomy are generated by a control policy that is able to achieve the task. Within a given environment there are potentially multiple tasks and therefore multiple policies able to achieve those tasks. The autonomy computes a confidence measure $\mathbf{c}$ for each candidate task and select its policy π associated with the most confident task. The autonomy commands $\mathbf{u}_r$ are generated by the policy π.

In our implementation the robot policies are generated using the Stable Estimator of Dynamical Systems (SEDS) algorithm, an approach based on demonstrations and formulated as a dynamical system [9]. The confidence $\mathbf{c}$ is formulated based on the agreement between the user and autonomy commands and the alignment of the robot's end-effector pose (position + orientation) with that of the final target pose,

$$\mathbf{c} = \mathbf{u}_h \cdot \mathbf{u}_r + e^{-\alpha d} + e^{-\beta\theta} \tag{2}$$

where d is the Euclidean distance, θ is a measure of the orientation alignment (computed using quaternion difference) between the current end-effector pose and the goal pose, and α and β are decay constants.

[1]The MICO is the research edition of the JACO arm which is used commercially within assistive domains. It is a 6-DoF manipulator with a 2-finger gripper.

B. Assistance Customization Schemes

Our target is to evaluate different schemes which dictate the autonomy adjustment in the assistive device—that is the value of the blending factor λ (Equation 1). In particular, two customization schemes are considered.

1) Customization using an Arbitration Function: This scheme involves arbitration between the user's control signal $\mathbf{u}_h$ and the robot's signal $\mathbf{u}_r$ through a function. Most arbitration functions in the literature [8] take a form as in Figure 4, where the arbitration is a function of some independent variable, often the robot's confidence $\mathbf{c}$ in its inference of the human user goal.

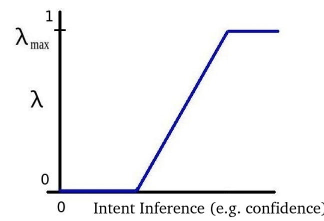

Fig. 4. Arbitration function to regulate autonomy adjustment

Instead of using predefined (fixed) arbitration functions to determine λ, we propose methods in which the user can change the very nature of the arbitration function using the customization interface, according to two paradigms:

How aggressively the robot takes control?
In this paradigm the user can control the aggressiveness of the robotic assistance, as a function of its confidence in the user's goal (Figure 5). The customization signal ϕ is set to modulate the slope of the arbitration function through a tunable confidence threshold c_{max} above which the robot assumes maximum control (keeping the initiation of assistance, c_{min} held fixed).

$$\phi = c_{max}$$

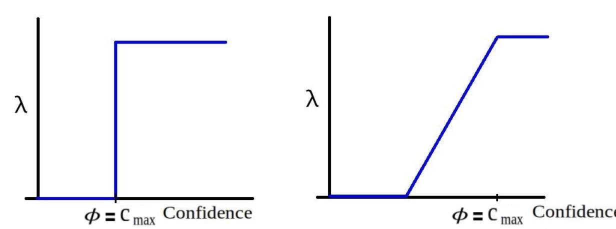

Fig. 5. Customization of how aggressively the robot takes control.

What is the maximum assistance the robot can provide?
In this paradigm the user can control the maximum level of robotic assistance, once the confidence threshold of c_{max} is reached. The customization signal ϕ modulates the maximum assistance level (Figure 6).

$$\phi = \lambda_{max}$$

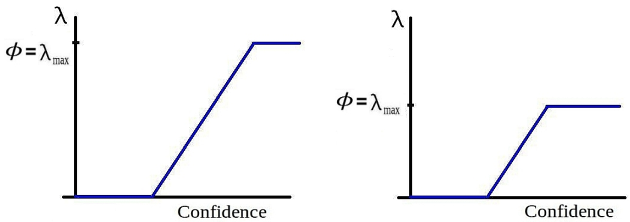

Fig. 6. Customization of how much assistance the robot provides.

These paradigms are dependent on the robot's confidence in the user's goal and have different effects on the blending factor λ, providing a wide customization spectrum in the hands of the user to decide the optimal arbitration function.

2) Direct Customization: In this scheme we propose a direct customization paradigm in which the user directly dictates, using the customization interface, the exact amount of control shared (Figure 7). This also allows for the context determination to be done solely by the user; that is, the assistance level adjustment is not dependent on the robot's confidence in the user's target.

$$\phi = \lambda$$

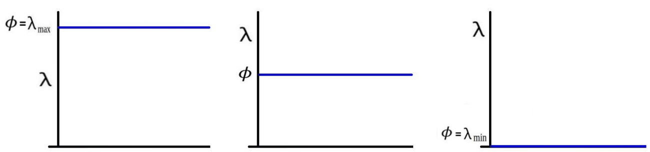

Fig. 7. Direct customization scheme

C. Planned Experiments

We will run a within-subjects study with people with motor-impairments and control subjects. The study will involve manipulation tasks using the MICO assistive robotic arm. The subjective measures will be interface design preference, online customization acceptance and autonomy adjustment scheme preference. These subjective measures will be collected by a self-reported questionnaire from the subjects. Our analysis will examine whether any of these factors generalize across users and tasks. The objective measures will be the time required and the number of mode switches for task completion, and the frequency of customization adjustments using the interfaces for each scheme.

V. Conclusion

Shared autonomy offers the possibility to facilitate the easier operation of assistive devices. However, it is likely that existing autonomy adjustment schemes do not generalize across users and tasks. Our insight to empower end-users to dictate the autonomy adjustment in an online manner has the potential to improve user satisfaction and adoption of intelligent assistive devices. We have proposed a suite of novel assistance customization interfaces, and our plans to evaluate a set of customization schemes with the interfaces. The aim is to evaluate acceptance and utility of the online customization and how both change with the form factor of the customization interface and the customization scheme.

VI. ACKNOWLEDGMENTS

Research reported in this work was supported by the National Institute of Biomedical Imaging and Bioengineering & National Institute of Child Health and Human Development under award number R01EB019335. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We thank Jessica Pedersen, OTR/L, ATP/SMS and Mark Felling for helpful discussions.

References

[1] K. M. Tsui, D.-J. Kim, A. Behal, D. Kontak, and H. A. Yanco, "I want that: Human-in-the-loop control of a wheelchair-mounted robotic arm," *Applied Bionics and Biomechanics*, vol. 8, no. 1, pp. 127–147, 2011.

[2] A. Jain and C. C. Kemp, "El-E: an assistive mobile manipulator that autonomously fetches objects from flat surfaces," *Autonomous Robots*, vol. 28, no. 1, pp. 45–64, 2010.

[3] J. Kofman, X. Wu, T. J. Luu, and S. Verma, "Teleoperation of a robot manipulator using a vision-based human-robot interface," *IEEE Transactions on Industrial Electronics*, vol. 52, no. 5, pp. 1206–1219, 2005.

[4] T. Debus, J. Stoll, R. D. Howe, and P. Dupont, "Cooperative human and machine perception in teleoperated assembly," in *Experimental Robotics VII*, 2001.

[5] S. Javdani, S. Srinivasa, and J. A. D. Bagnell, "Shared autonomy via hindsight optimization," in *Proceedings of Robotics: Science and Systems*, July 2015.

[6] E. You and K. Hauser, "Assisted teleoperation strategies for aggressively controlling a robot arm with 2d input," in *Proceedings of Robotics: Science and Systems*, 2011.

[7] D.-J. Kim, R. Hazlett-Knudsen, H. Culver-Godfrey, G. Rucks, T. Cunningham, D. Portee, J. Bricout, Z. Wang, and A. Behal, "How autonomy impacts performance and satisfaction: Results from a study with spinal cord injured subjects using an assistive robot," *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, vol. 42, no. 1, pp. 2–14, 2012.

[8] A. Dragan and S. Srinivasa, "Formalizing assistive teleoperation," in *Proceedings of Robotics: Science and Systems*, 2012.

[9] S. M. Khansari-Zadeh and A. Billard, "Learning stable nonlinear dynamical systems with gaussian mixture models," *IEEE Transactions on Robotics*, vol. 27, no. 5, pp. 943–957, 2011.