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Review Article

Computer Access Technologies for Controlling Assistive Robotic Manipulators: Potentials and Challenges

Ka HW[1,2]*, Ding D[1,2] and Ravishankar S[3]
[1]Human Engineering Research Laboratories, Department of Veterans Affairs, Pittsburgh, PA, USA
[2]Department of Rehabilitation Science and Technology, University of Pittsburgh, Pittsburgh, PA, USA
[3]Robotics Institute, Carnegie Melon University, Pittsburgh, PA, USA

***Corresponding author:** Ka HW, Department of Rehabilitation Science and Technology, University of Pittsburgh, 6425 Penn Ave. Suite 400 Pittsburgh, PA, USA

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Abstract

One of the most challenging barriers to a successful application of the assistive robots is how to enable users who have special needs to interact with the robot aids in an efficient and comfortable manner, since the conventional control method using a traditional joystick combined with buttons and/or knobs demands fine motor control and good dexterity resulting in cognitive and physical workload. Adopting computer access technology, which has provided an alternative means to allow people who have a wide range of special needs to independently access their computer, can be a practical solution to this issue. In this paper, we reviewed and discussed the potentials and challenges of computer access technologies as an alternative control method for controlling assistive robotic manipulators, focusing on most widely adopted interventions in the clinical settings, including alternative pointing, keyboard-only access, switch scanning interface and speech recognition.

Keywords: Alternative interaction method; Human-machine interaction; HCI; Assistive technology; Assistive robotic manipulator

Abbreviations

AD: Activities of Daily living; CAT: Computer Access Technology; DOF: Degrees Of Freedom; SCI: Spinal Cord Injury

Introduction

With the technology advancement and cost reduction in commercial robotics technology, assistive robotic manipulators hold great potential to assist individuals with physical disabilities with a range of activities of daily living (ADL) [1-6]. However, one of the most challenging barriers to a successful application of the assistive robots is how to enable users with disabilities to interact with the robot aids in an efficient and comfortable manner. Conventionally, the most widely adopted solution for commercially available assistive robotic manipulators is to use a traditional joystick combined with buttons and/or knobs. However, people who have severely impaired motor functions or have a combination of multiple disabilities have found it difficult or impossible to independently operate the robotic aids. As a practical solution to accommodate the individuals who belong to this population, some researchers and research groups adopted Computer Access Technology (CAT) as an alternative control method for assistive robotic manipulators [7-14], because it has long provided an alternative means to allow people who have a wide range of special needs to independently access their computer. However, most of their work were not only based on non-disabled participants, but also their primary focus were on improving dynamics and kinematics of the robots rather than on developing alternative control methods. In this article, we review the CAT as an alternative control method for controlling assistive robotic manipulators currently available on the market, and discuss its potentials and challenges in applying the technology to assistive robotic manipulation.

Assistive Robotic Manipulator

Over a couple of decades, several assistive robotic manipulators have been developed and evaluated to help people with disabilities to perform ADLs more independently and efficiently. However, currently only few of them are available on the market. Two most commonly used assistive robotic manipulators include Manus ARM (by Exact Dynamics) and JACO manipulator (by Kinova), both of which are wheelchair mountable robotic arms with more than six degrees of freedom (DOF) equipped with a multi fingered gripper. In most clinical applications, they are controlled by a joystick combined with buttons and/or knobs. To maximize the capacity of robotic manipulation, the robotic manipulators provide two different types of control mode: Cartesian mode and joint-wise mode or angular mode. In the Cartesian mode, the user only controls movements of and around the hand, and the different joints are piloted automatically using onboard kinematics. In the joint-wise mode, the user is responsible for moving the assistive robotic arm joint by joint by specifying angles to each of them. In this mode, however, it is possible for the arm to hurt itself, unless the user has enough knowledge about kinematics and dynamics. Thereby, in real world situation, users prefer to rely on the Cartesian mode because it is more intuitive than the angular mode. In most clinical applications, they are controlled by a joystick combined with buttons and/or knobs, which demands fine motor control and good dexterity imposing cognitive and physical overload.

In order to efficiently operate a robotic manipulator, two types of command sets are required: directional and task-based commands. Directional commands are used to make translational/rotational movements of an assistive robotic manipulator (e.g., “move up”, “move down”, “move left”, “move right”, “move forward”, and “move backward; “rotate up”, “rotate down”, “rotate left”, and “rotate right”). Task-based commands are used to perform primitive robotic manipulations (e.g., “open hand”, “close hand”, “push it”, “tap it” and “stop”). Thus, in terms of actual user interface design, as a minimal requirement for successful robotic manipulation, at

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least, the following operation commands, which can be divided into several subcategories (translational, rotation, finger, and safety), are necessary:

- Translational operation
    1. Up / Down o Left / Right
    2. Forward / Backward
- Rotational operation
    1. Horizontal orientations
    2. Vertical orientations
    3. Pivotal rotations
- Finger operation
    1. Open
    2. Close
- Safety
    1. Stop
    2. Home / Retract preset positon

Therefore, when applying CAT to assistive robotic manipulation, it is necessary to see if it has the potential to cover the above commands. Moreover, taking into account the fact that the working space of assistive robot manipulator (3 dimensional real physical space) is much different from that of CAT (2 dimensional virtual space on the screen), careful considerations should be given.

Computer Access Technology as an Alternative Control Method for Robotic Manipulator

The spectrum of CAT is very wide, ranging from relatively simple and inexpensive devices like a single switch, trackballs and small-footprint keyboards to sophisticated and high-cost technologies like automatic speech recognition, head pose or eye gaze tracking, and brain-computer interfaces. However, in this paper, we limit our focus to most widely adopted CAT interventions in the clinical settings, including alternative pointing, keyboard-only access, switch scanning interface and automatic speech recognition.

Alternative pointing methods

When controlling the robotic manipulator, users actually control the movement of and around an invisible reference located in the center of the end effector. For example, when the command is given to the robot to go forward, the end effector will have a linear displacement parallel to the mounting axis. This suggests that several existing alternative pointing methods for on-screen object manipulations adopted in computer access interventions (e.g., trackball, isometric joystick, and head-controlled mouse emulator) can also be used for assistive robotic manipulation.

Trackball: A trackball is a pointing device which looks like an upside-down mouse consisting of a ball and two or three buttons. The ball is held by a socket containing sensors to detect rotational displacement of the ball and convert it into a linear displacement of the on-screen cursor. The buttons are used for clicking operations. It requires less range of motion and occupies less space than a traditional pointing device. The user rolls the ball with the thumb, fingers, or palm to move the on-screen cursor. Once the cursor is within the target of interest, he or she presses the button to perform the desired pointing operations (e.g., single-click, double-click, and click-and-drag). By separating the action of moving the cursor from the action of pressing buttons, it prevents users from unintentional clinking operations.

Adopting the trackball as a control device for assistive robotic manipulators has some advantages over the conventional control method. For example, the user does not need to keep griping and stabilizing the control device while performing robotic manipulation tasks. In addition, by separating the directional commands controlled by the ball from the task-based commands controlled by the buttons, it keeps users from the unintentional activation of robotic commands. Thus, it is good for individuals who have difficulty keeping a conventional joystick handle being pushed when performing directional commands. Once the end-effector is located at the desired position or when it is necessary to switch to the different operation mode (e.g., translational, rotational, and finger), the user can perform the operation of interest by pressing the buttons attached to the trackball. Laffont and colleagues adopted a trackball as one option of the control methods for controlling their wheelchair mounted robotic manipulator through graphical user interface [10]. In the research, 12 disabled participants were asked to grasp six objects placed around the wheelchair, selecting the target object on the screen by using the trackball. The significant lower success rate and longer completion time were reported for the participants compared to the control group. But a high satisfaction rate was reported for this population, suggesting that the graphical user interface operated by the trackball can be used as an alternative control method for assistive robotic manipulators for some people with disabilities. However, the trackball can be inappropriate for users with poor dexterity, because it still takes advantage of an individual's ability to accurately control the ball to move the end effector.

Isometric joystick: An isometric joystick, also called a force joystick or stiff stick, is an alternative to a general computer mouse and a conventional joystick. It converts applied force into a proportional electrical output resulting in the magnitude and direction of the cursor on the screen. For performing pointing operations, like a trackball, external buttons are used. In general, it takes less footprint and homing time to switch between a stick and buttons compared to the conventional pointing devices [15].

Applying the isometric joystick to assistive robotic manipulation has almost the same advantages and disadvantages as the trackball. However, while the isometric joystick requires less range of motion compared to the trackball, it takes more practice time and fine motor control for the user to achieve expert control.

Head-controlled mouse emulator: Head-controlled mouse emulators, also called head-controlled pointers, use the position of the head to control the on-screen cursor, translating changes in the user's neck rotation, flexion, and extension into directly proportional movements of the mouse cursor. Some systems provide alternative physical switches for pressing buttons such as sip and puff or touch switches. For those who cannot use physical switches, emulation software, such as a dwelling interface, is often used. In order to specify a pointing command, users place the screen cursor within the boundary of the on-screen target for a predefined period of time, instead of pressing buttons [16]. In general, a head-controlled mouse emulator requires significantly more training time compared to other pointing devices.

Adopting this technology as an a control method for controlling assistive robotic manipulators is beneficial for users who have limited arm range of motion, have limited grip strength, and have poor hand/arm control, providing them with hands-free operation. Several researchers integrated the head-controlled mouse emulator into their research [9-11,13,14]. For example, Chen and colleagues evaluated a head-controlled pointer with force feedback to control a robotic manipulator [9]. For the research, six able-bodied participants were recruited and asked to perform three basic manipulation tasks such as touching two targets on a board, turning pages, and drawing two diagonal lines, and the performance was measured based on Fitts' law [17,18]. Another research conducted in the University of Massachusetts-Lowell reported that one of the participants performed object-retrieving tasks by selecting an object on the screen using a head-controlled pointer [13].

The biggest challenge with applying head-controlled mouse emulators to assistive robotic manipulation is keeping the user who cannot operate a physical switch from making unintentional movement while issuing task-based commands. With other alternative pointing devices, users can remove their body parts from the device to prevent further movements. However, with a head-controlled pointer, it is not possible to separate the action of directional commands from the action of task-based commands. Another concern with adopting a head-controlled mouse emulator as a control method for robotic manipulators is the increased stain on the user's neck. Thus, extended training times are advised.

Keyboard-only access

A computer can be used entirely from the keyboard without using any sort of pointing devices. There are several advantages to using the keyboard, instead of using the pointing devices [19]. For example, it does not require moving the user's hands from the keypad to the pointing device. It is also not affected by both the size and the distance of on-screen targets. In addition, keystrokes are faster than mouse movements [19]. Moreover, if the user can write a macro which is a sequence of commands for performing a task, it is possible to automate repetitive and fatiguing tasks [20-22]. Thus, most of the modern computer operating systems provide the users with the keyboard-only access as a built-in feature named shortcut. It is particularly useful for individuals with visual impairments who are using screen reader and for those who are using an augmentative communication device for computer access.

Assistive robotic manipulation can also be performed only by the keyboard. In particular, for those who have poor pointing and targeting skills or who do not have fine motor control can benefit from it. For example, they do not need to move their hands from the joystick to the keypad; it is not necessary to perform direct directional operations requiring fine motor control; it is faster than pointing device operation; and it is possible to automate a complex task with a single key press, recording a series of operations. For these reasons, Manus ARM provides the users with a 4x4 keyboard consisting of numbers and letters. Using the keypad users can fully control the robot manipulator. Researchers working at the Forschungsinstitut Technologie-Behindertenhilfe in Germany tested the usability of this 4x4 keypad [23,24]. Participants with different disabilities were asked to drive the robotic manipulator to a work position and build a tower of three wooden blocks. Eight out of the thirteen participants completed the task. Moreover, they also reported that two most skilled participants evaluated the keyboard-only access with their own choices of typical ADL tasks (e.g., self-care, eating, drinking, and pouring out liquid, opening doors and drawers, grabbing and handling objects, retrieving papers out of a file, and lifting up objects from the floor/ground), even though no clinical results were provided.

However, keyboard-only access has also some obstacles. For example, it is not so much intuitive as the pointing device. In addition, for task-based commands, there can be significant cognitive load and learning curve. Moreover, while the macro technique can greatly simplify complex tasks, it can be not only less flexible than direct operation [21], but the automated function can also raise a safety issue in some situations, unless the user does not know how to activate emergency stop.

Switch scanning interface

Users who cannot use adapted keyboards or pointing devices may benefit from using a switch, which is something that opens and closes to control the flow of electrical current, combined with a scanning interface referred to as the process of choosing items from a selection set. Switch scanning interface is generally used as an alternative input method for computer access and augmentative communication devices. In switch scanning interface, items or groups of items are highlighted one at a time in turn at a certain interval. When the desired item is highlighted, the switch hit is made to select and activate the item. The number and depth of items determines the number of switch presses required to activate a desired item. Depending on the user's availability, a switch can respond to a different type of input modality, such as physical pressure, air pressure, tilt, proximity, eye blink, muscle activity, and auditory cue.

In general, switch scanning interface is known as one of the slowest ways to operate an assistive technology. However, it still has potentials to enable wider range of physically challenged individuals to benefit from assistive robotic manipulators, because it provides an affordable and reliable option, imposing minimal motor demands. For example, individuals who cannot use a conventional joystick and/or a keypad, and those who have limited vocal abilities, can operate assistive robotic manipulators, only if they have a single reliable movement to activate a switch, making each command of the command set highlighted in turn at a certain interval. When the desired control command is highlighted, the user hit the switch to activate the command. In a study conducted by DuPont Hospital for Children, 3 out of 9 participants could complete three different robotic manipulation tasks defined by Jebsen Hand Test, Block and Box Test, and Minnesota Rate of Manipulation Test, using a switch scanning interface [12].

Besides its slowness, challenges to applying switch canning to assistive robotic manipulation include: it can impose cognitive load and learning curve; and it requires an additional display to present the scanning interface. Ka and Simpson attempted to reduce the cognitive load by providing the user with context sensitive scanning interface, which automatically switch between different modes, based on context awareness algorithm using sensor input [25].

As another unique switch based approach for controlling assistive robotic manipulators, Morse code can be considered, because it can not only overcome the slowness of the scanning interface, but can also eliminate the need of additional display. Applying Morse code to assistive robotic manipulation has many advantages. For example, it requires minimal motor control; it does not require a scanning interface to present robotic commands; and it can thereby become a sub-cognitive process like touch typing. However, at the same time, Morse code has its own challenges, including a limited number of clinicians who know Morse code, a steep learning curve for new users, no visual feedback, the need to accurately time switch presses and increased cognitive effort. Among these challenges, in particular, the need of accurate switch press timing is challenging to people with limited motor functions. For example, the standardized Morse code defines timing rules to specify characters or commands. For example, the duration of a dash is three times as long as the duration of a dot. Each dot or dash is followed by a short silence, equal to the dot duration [26]. This can cause people with limited motor functions to make many errors. In order to resolve this issue, Ka and Simpson adopted the concept of threshold and time-out [27]. The distinction between a dot and a dash is based on whether the duration of each switch press exceeds a time threshold. Since each command is the same bits long, so commands cannot be accepted prematurely. If the time after a switch press exceeds a pre-determined threshold, the composing command is discarded [27].

Speech recognition

Speech recognition translates spoken words into digital text. Using speech recognition, users can not only dictate and edit text, but can also issue voice commands (e.g., “click recycle bin”, “switch application”, “scroll up”, “shut down”) to control their computers. Speech recognition has typically two different modes: discrete and continuous mode. While continuous mode allowing the user to use multiword phrases is appropriate for automatic dictation, discrete mode requiring the user to pause between each word is more often adopted for systems for issuing voice commands, because it does not necessarily require the users to train the system to recognize the user’s speech prior to use [28]. Discrete speech recognition is also useful for people who have difficulty speaking clearly and consistently [29].

Adopting speech recognition technology to control the assistive robotic manipulator offers several benefits to users, who cannot take advantage of conventional control methods, such as individual with tetraplegia. It can not only provide completely hands-free operation, but also helps a user to maintain a better working posture and allows him or her to work in postures that otherwise would not be effective for operating an assistive robotic manipulator (i.e., reclined in a chair or bed). A study conducted at the Palo Alto Veterans Affairs Spinal Cord Injury Center adopted speech recognition as a control method to evaluate a desktop vocational assistant robotic workstation [8]. Twenty four participants with high level SCI were asked to perform a range of ADL tasks. The performance was measured based questionnaires, interviews, and observer assessments. It was reported that the majority of participants had positive attitude toward the desktop assistant robot controlled by speech recognition.

Speech recognition has some challenges in applying to assistive robotic manipulation, as well. For example, the users are required to have a sufficiently strong and consistent voice and cognitive skills. Speech recognition takes longer to complete directional commands compared to other methods, due to frequent explicit use of a stop command. In addition, it is not easy to control the speed of the robot movement. As a solution to address these issues, integrating vision-based semi-autonomous features is recommended.

Discussion

Through the review of CAT as an alternative control method for controlling assistive robotic manipulators, we found it has potential power to accommodate wider range of individuals with severe physical disabilities who have found it difficult or impossible to independently operate the robotic aids due to their lack of access to the conventional control method. However, in order for the application of CAT to be clinically successful, besides technical aspects of CAT, it is necessary that some other important factors should also be addressed.

First, it is important to develop appropriate quantitative methods to evaluate and document users’ abilities and specific difficulties with assistive robotic manipulation. While there are lots of ways to measure the performance associated with CAT itself, no standardized assessment process for assistive robot manipulation is not developed yet. Traditionally, Fitts’ law [17,18] has been adopted for measuring assistive robotic interaction tasks. However, Fitts’ law ignores both mental preparation and perceptual activity, and only describes motor activity. Hence, there is a possibility to miss important information. Developing a new assessment tool based on more comprehensive user modeling techniques to more accurately represent assistive human-robot interaction is essential.

Second, it is necessary to develop and provide training programs for both clinicians and clients. In the clinics, many service providers do not have training in CAT [30-32], and it can also be hard for them to remain knowledgeable about CAT when it is not their primary focus [33,34]. In addition, many users with disabilities do not know how to make adjustments to the settings associated with CAT and the assistive robotic manipulator, which can be time-consuming and confusing [35,36]. This may lead to technology abandonment. A study of 115 individuals with disabilities who received 136 assistive technology devices over five years reported a total abandonment rate of 32.4% [37]. Finally, as always, when making decision about prescribing appropriate CAT for assistive robotic manipulation, it is crucial to rely on user-centered team-based approach involving both the user and other stakeholders. Using that approach enables the service provider not only to identify the user’s main goals and priorities, but also to get important information on all aspects of the user’s life and environment that will have influence on the use of assistive robotic manipulator.

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