Assistive Mobile Manipulation for Self-Care Tasks Around the Head

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***Abstract*— Human-scale mobile robots with arms have the potential to assist people with a variety of tasks. We present a proof-of-concept system that has enabled a person with severe quadriplegia named Henry Evans to shave himself in his own home using a general purpose mobile manipulator (PR2 from Willow Garage). The robot primarily provides assistance by holding a tool (e.g., an electric shaver) at user-specified locations around the user's head, while he/she moves his/her head against it. If the robot detects forces inappropriate for the task (e.g., shaving), it withdraws the tool. The robot also holds a mirror with its other arm, so that the user can see what he/she is doing. For all aspects of the task, the robot and the human work together. The robot uses a series of distinct semi-autonomous subsystems during the task to navigate to poses next to the wheelchair, attain initial arm configurations, register a 3D model of the person's head, move the tool to coarse semantically-labeled tool poses (e.g, "Cheek"), and finely position the tool via incremental movements. Notably, while moving the tool near the user's head, the robot uses an ellipsoidal coordinate system attached to the 3D head model. In addition to describing the complete robotic system, we report results from Henry Evans using it to shave both sides of his face while sitting in his wheelchair at home. He found the process to be long (54 minutes) and the interface unintuitive. Yet, he also found the system to be comfortable to use, felt safe while using it, was satisfied with it, and preferred it to a human caregiver.**

I. Introduction

A. Background

Persons with severe upper-body motor impairments have limited control of their hands or arms and often require assistance performing activities of daily living (ADLs) that involve manipulating tools near their heads, such as eating, brushing hair, and shaving.

Human-scale mobile robots with arms have the potential to assist diverse users with a wide variety of tasks. The robots' mobility gives them a large dexterous workspace. Unlike desktop robots and wheelchair-mounted robot arms, they can perform tasks away from the user and do not need to occupy valuable space near the user when inactive. They also have the potential to be economical general-purpose consumer devices rather than niche medical or assistive devices. However, these benefits come at the cost of higher complexity (e.g., more degrees-of-freedom and sensors) than specialized robotic devices.

Within this article, we present research that we conducted as part of the Robots for Humanity project, which was a collaborative project involving our lab, Willow Garage, Oregon State University, and Henry and Jane Evans [1]. Henry Evans has severe quadriplegia as the result of a brain-stem stroke in August 2002. His desire to use the PR2 as an assistive device led to the establishment of the project, which focused on the potential for a PR2 robot from Willow Garage to provide assistance to Henry and others with severe motor impairments. The PR2 is a commercially available, general-purpose mobile manipulator that was not specifically designed as an assistive device.

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Fig. 1. **Shaving Using a PR2 Robot:** Henry Evans, a man with quadriplegia, using the PR2 robot to shave the left side of his face while he sits in his manual wheelchair in the living room at his home. He uses a head-tracking mouse on the laptop in front of him to operate the system. The robot is holding a mirror and an electric shaver.

As part of an earlier article on the Robots for Humanity project, we presented a high-level description of previous versions of our system for self-care tasks around the head, which Henry had used to shave his chin and one cheek while in a meeting room at Willow Garage [1]. This earlier report described our efforts up to February 2012, including a description of system components operating in isolation. Here, we present a detailed description of a later, fully-integrated system from June 2012 along with thorough results from a trial during which Henry shaved both sides of his face while sitting in his manual wheelchair in the living room of his home.

We conducted this research with approval from the Georgia Institute of Technology Institutional Review Board (IRB), and obtained informed consent from all participants.

B. System Overview

Our approach is to use robotic intelligence and human-in-the-loop control to combine the complementary capabilities of the robot and the human user. The user operates the robot via a web-based interface that can be run from a modern web browser. This gives the user a variety of options for the computer and OS used to control the robot. In addition, it only requires control of a standard mouse cursor and left click button via the user's preferred assistive interface. With our system, Henry used an off-the-shelf head tracker from Madentec and the buttons on a standard mouse. The web-based interface was also useful during development, since it enabled Henry to test the system in our lab in Atlanta, Georgia from his home in California.

The robotic system we present in this paper consists of five main semi-autonomous subsystems that the user initiates, monitors, and guides (Fig. 2). The first subsystem navigates the robot to predefined poses of the robot's mobile base with respect to augmented reality tags (ARTags). The second plays back prerecorded arm trajectories to put the robot's arms in appropriate initial configurations. The third moves the tool to coarse, semantically-labeled poses relative to a 3D model registered to the user's head. The fourth enables the user to finely move the tool via an ellipsoidal coordinate system around this 3D model. The fifth monitors forces applied to the tool, withdrawing it if the robot detects inappropriate forces.

Using the complete system, Henry has commanded the PR2 to reach locations across both sides of his face, including under his chin, with an electric shaver, enabling him to shave his entire face. With minor modifications, the system would likely enable Henry and others to perform additional tasks around their heads. For example, Henry used earlier versions of our system to brush his hair and scratch an itch, and tasks such as scratching an itch and wiping with a cloth tend to be less sensitive to the pose of the tool than shaving [1]. The shaver tool is the head of a Panasonic ES-LA63-S electric shaver, modified so the user can toggle power to the shaver (Fig. 6D) via an Arduino micro-controller connected to the robot. The robot also holds a mirror with its other arm so that the user can monitor task progress.

We have released code and hardware designs associated with our system as open source software and open hardware with liberal licenses [2].

C. Assistance by Holding a Tool at User-specified Locations

Kinematics and contact forces play especially important roles in many ADLs. A task like shaving with an electric shaver requires moving a specialized tool appropriately with respect to a person's head and making contact with appropriate force [3]. We have designed our system for people who have upper-body motor impairments but can still move, and have sensation across, their heads. The robot is primarily responsible for holding the tool near the person's head, while the person moves against it. This gives users direct control of the physical interaction, allowing them to adapt the interaction to their preferences.

Given this division of labor, *the primary challenge for the robot is to move the tool to a desired pose with respect to the user's head*. Since we assume that the mobile manipulator does not start beside the user, the robot first drives to the user's wheelchair. To position the robot so that it can reach both sides of Henry's face, we recorded two poses for the robot's mobile base relative to ARTags affixed to each side of Henry's wheelchair. Henry first shaves one side of his face and then the other using these two poses. Once at each pose, the robot neither moves its base nor raises or lowers its torso.

After the robot has navigated to one of these poses, it must move the tool to a desired pose relative to the person's head. In our system, the user specifies the desired pose in two steps. First, the user selects a coarse, semantically-labeled region of the head to which the robot autonomously moves the tool (e.g., cheek or chin). Once at this location, the user can finely position the tool by moving it incrementally in an ellipsoidal coordinate system, which simplifies changing the distance between the tool and the user's head as well as moving around the user's head while keeping the tool properly oriented.

To improve safety and comfort, the robot monitors the forces applied to the tool using a wrist-mounted, six-axis force-torque sensor. If it detects inappropriate forces, it moves the tool away from the person's head. This gives the person direct control of the contact forces within a task-appropriate range. We selected this method after trying alternatives, such as force control and impedance control. Unlike a person providing assistance, the robot can hold a tool steady for long periods of time without difficulty and can maintain a consistent pose in the presence of applied forces.

II. Related Work

Many robots have been used to provide assistance with tasks around a person's head. These robots differ in their mobility, commercial availability, the range of tasks with which they can assist, the people they can assist, their effectiveness, their usability, and the thoroughness with which they have been evaluated. We will briefly discuss select examples from this large body of related work.

Many robots that have provided assistance around a person's head have been fixed to a surface. For example, the CEA/MASTER RAID device [4], [5], the Desktop Vocational Assistance Robot (DeVAR) [6] and later ProVAR [7], the JHU/APL arm [8], Handy 1 [9], [10], and MySpoon [11] are forms of desktop robots that require the person to be next to them in a predefined pose. Feeding has been a common task with which these robots assist. For example, the commercially available MySpoon is specifically designed for feeding, while the commercially sold Handy 1 was intended for more general assistance and supported an electric shaver and toothbrush.

For people who regularly use wheelchairs, wheelchair-mounted robot arms (WMRA) provide another option. WMRAs are fixed to the user's wheelchair, which simplifies challenges associated with achieving a pose of the robot arm relative to the user's body. The JACO and iARM are commercially available WMRAs that allow the user to directly control the arm and gripper for general-purpose use, including self-care tasks. Researchers have sought to simplify operation of these systems via semi-autonomous control, such as in the context of picking up objects [12], [13]. The research robot RAPUDA is a WMRA with a

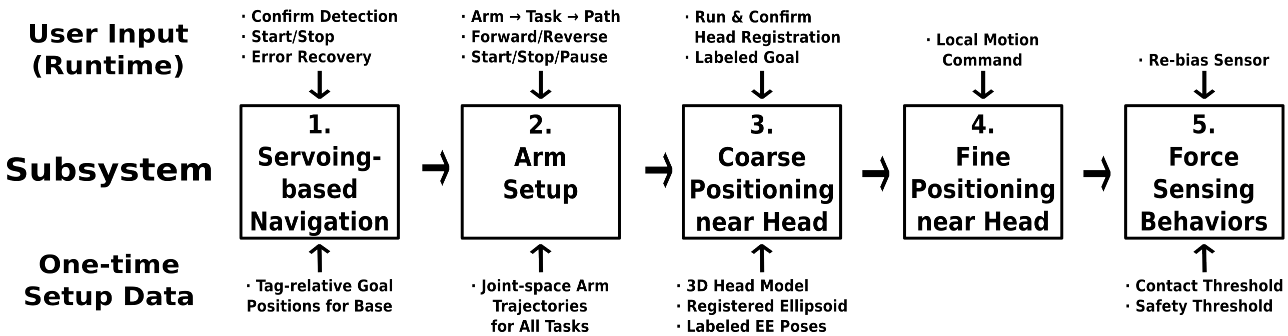

Fig. 2. **System Block Diagram:** Using the system involves progressing through each subsystem in this diagram from left to right. If the task requires that the robot navigate to more than one location, this sequence of subsystems will be used at each location. For example, Henry Evans used a location on each side of his wheelchair when shaving, and hence moved through this sequence twice. As shown, each subsystem uses a combination of prerecorded data and live user input.

novel telescoping design, which may make it appropriate for a variety of tasks, although [14] did not report on tests with motor-impaired users acting on themselves for safety reasons.

There are significantly fewer examples of mobile manipulators being used to provide assistance around a person's head. The MOVAID system focused on performing household tasks, such as cleaning and preparing meals [15]. The 'Care-O-Bot' assistive robot has been through many iterations [16], [17], but has not emphasized self-care tasks. [18] reports that the KARES II system used multiple forms of user input and provided assistance with shaving, but the details of how people used the system to shave are unclear.

[19] presents the Asibot system, which has been used for assistance with self-care tasks around the head, including wiping and scratching. This system uses a novel approach that involves the robot moving between specialized mounts installed in the environment, such as from a mount on the user's wheelchair to a mount by the bathroom sink. As such, it shares properties of desktop robots, WMRAs, and mobile manipulators.

III. Ellipsoidal Coordinate System (E-space)

Our system uses an ellipsoidal coordinate system to move the tool around the user's head. When first setting up the system for a user, we fit an ellipsoid to a 3D model of the user's head and then attach it to this 3D model. Prior to moving the tool near the user's head, the robot registers the 3D model to the user's head via a Kinect sensor, which results in the ellipsoid and its corresponding ellipsoidal coordinate system being registered to the user's head. The robot then moves its tool with respect to this ellipsoidal coordinate system (E-space).

More specifically, we use prolate spheroidal coordinates [20] for shaving. For other tasks, such as brushing hair, oblate spheroidal coordinates might be more appropriate. Every point in Cartesian space, (x, y, z), can be represented by a triple corresponding to latitude ϕ, longitude θ, and height h (Fig. 5), where

$$\begin{aligned} x &= l \ \sinh h \ \sin\phi \ \cos\theta \\ y &= l \ \sinh h \ \sin\phi \ \sin\theta \\ z &= l \ \cosh h \ \cos\phi. \end{aligned}$$

For any particular height, h, the Cartesian surface parameterized by (ϕ, θ) is an ellipsoid with two minor principal axes of equal length, $l \sinh h$, and a major principal axis of strictly greater length, $l \cosh h$. Increasing l makes these ellipsoids more elongated over the volume of E-space used by the robot. When fitting an ellipsoid to the 3D model of the user's head, we translate it, rotate it, and adjust l using rviz and interactive markers [21].

The mapping from E-space to Cartesian space, $\mathbb{E}(\phi, \theta, h) \rightarrow (x, y, z)$, is bijective and smooth almost everywhere (except at the z-axis). In addition to a Cartesian position, the triple (ϕ, θ, h) defines a canonical orientation matrix

$$O_{\mathbb{E}}(\phi, \theta, h) = \left[-\frac{\partial \hat{\mathbb{E}}}{\partial h} \quad -\frac{\partial \hat{\mathbb{E}}}{\partial \theta} \quad -\frac{\partial \hat{\mathbb{E}}}{\partial \phi} \right]_{\phi, \theta, h} \in SO(3).$$

Thus, the X-axis of the frame points inward toward the center of the ellipsoid, the Y-axis points along changing longitudes, and the Z-axis points along changing latitudes. When using E-space, all tool poses are specified by a (ϕ, θ, h) triple and an offset orientation O_{off} relative to the canonical orientation. The tool's pose (p, O) in Cartesian space would thus be computed as $p = \mathbb{E}(\phi, \theta, h)$, $O = O_{\mathbb{E}}(\phi, \theta, h) * O_{\mathit{off}}$

The robot performs E-space motions using a Cartesian task-space controller. At a rate of 20Hz, the robot sends Cartesian end-effector poses to the controller to achieve smooth motion based on a minimum-jerk trajectory. The task-space controller is a PD J^T controller modified so that the gains are specified in the end-effector frame [22]. The robot uses lower gains in the direction the tool is pointing ($\sim$ 3 N/cm) than the perpendicular directions ($\sim$ 6 N/cm). Thus, the tool will tend to remain at the same location relative to the surface of the user's head, but will be more compliant with respect to contact forces normal to its active surface (e.g., the head of the electric shaver).

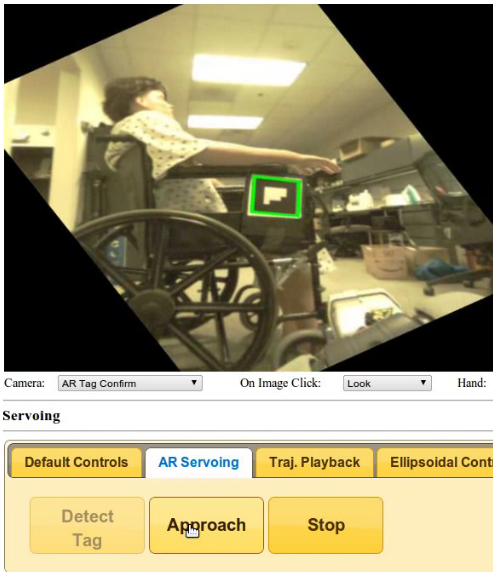

Fig. 3. **AR Servoing Interface:** A green box highlights the detected tag. The user can now command the robot to approach a recorded pose, stopping it at any time.

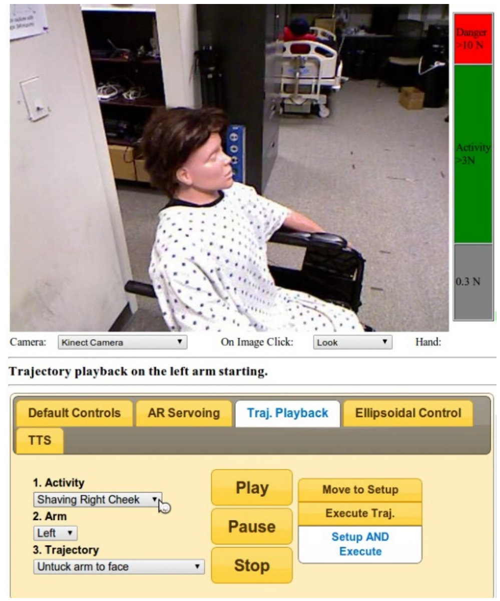

Fig. 4. **Trajectory Playback Interface**

IV. Detailed Description of the Subsystems

Our system consists of distinct subsystems that should be appropriate for reuse in a variety of tasks. One subsystem is active at any given time and each subsystem has its own interface elements. The user completes a task through ordered use of the subsystems, providing input as necessary. The web-based interface consists of a live video feed from the robot that can be used by each of the subsystems for user input and to provide feedback to the user (Figs. 3, 6). In this section, we describe each subsystem in detail.

A. Navigate to Poses Relative to the Wheelchair

For our system, the robot must move the tool to user-specified locations near the user's head. In spite of their length, the PR2's arms have a relatively small workspace suitable for assisting with tasks around the user's head. This is due in part to the robot's base protruding in front of the arms, which restricts the robot's ability to move its arms close to the head of a user who is sitting in a wheelchair. In addition, motion of the robot's base is difficult to perform efficiently and carries risk, since the PR2 is heavy, the powered casters can produce high torques, and the base lacks bump sensors.

Due to these factors, we designed the system so that the mobile base moves to predefined poses with respect to the wheelchair and remains stationary while moving its arms. While its mobile base is in motion, the robot keeps its arms tucked in and monitors their joint torques to serve as bump sensors. If the robot detects a bump, it stops and informs the user. At any time, the user can directly drive the robot via a simple interface. However, automated positioning of the mobile base is important due to the limited range of base poses from which the robot can successfully reach the user's face.

Through trial and error we found one pose on each side of Henry's wheelchair, that, together, enabled the robot to reach all of Henry's face. To accurately position the base so that Henry's head is in a kinematically favorable region of the robot arm's workspace, we attach ARTags to each side of Henry's wheelchair. This allows the robot to achieve predefined poses with good precision and accuracy relative to the wheelchair using visual servoing.

The user interface presents buttons to initialize ARTag detection and to start and stop base servoing (Fig. 3). The view from the camera in the robot's forearm, rotated to remain upright, is overlaid with colored boxes highlighting detected ARTags. The user commands the robot to detect tags, confirms the detection of the appropriate tag in the camera view, and then initiates visual servoing, which proceeds slowly to a prerecorded planar pose of the mobile base relative to the tag, and therefore, to the wheelchair and user.

B. Move Arms to Initial Configurations

At many points, it is useful to play back prerecorded, task-specific arm trajectories (see Figure 4). For example, after navigating to the wheelchair, the robot moves its arms, holding the mirror and tool, to predefined configurations to give the user a view of his/her head from the mirror and bring the tool to an initial pose for reaching. This system also prepares the arms for navigating by tucking them next to the body and positioning the forearm camera to view the ARTag for visual servoing. Also, trajectories may be played in reverse, which is used for tucking the arms in again after shaving the first side of the user's face.

We recorded the trajectories as an able-bodied person moved the arm through desired motions by sampling joint configurations at 20 Hz. When replayed, if the arm is not near the initial configuration of the desired trajectory, the robot linearly interpolates from the current joint angles to the beginning of the trajectory before following the trajectory.

The robot plays the trajectories slowly, with low proportional gains at its torque-controlled joints to make its arms compliant. The interface allows the user to start, pause/resume, and stop a playing trajectory at any time. Drop-down menus guide the user in selecting the task of interest, the desired arm to move, and then the specific relevant trajectory to follow, as well as whether to play that trajectory forward or backward.

C. Coarsely Move the Tool to Semantically-labeled Poses

Our system uses a coarse-to-fine strategy to move the tool to a desired pose near the user's head. To coarsely position the tool, the user first selects the name of a facial region from a drop-down menu to command the robot to move the tool near that region. For this capability to function, the robot needs an estimate of where the named region is located.

1) Head Registration: Since a person's body pose varies with respect to a wheelchair, the robot registers a head model to decide where to move the tool. Specifically, the robot collaborates with the user to register a 3D head model to his/her head in a neutral pose (i.e., head held upright). This is a pose that Henry can maintain comfortably and from which he can move his head well.

When setting up the system, we create a model specific to the user. First, we place the robot in the base position from Sec. IV-A to which it will navigate for shaving, since this is the position from which the robot will observe the user's head during use. We then capture a 3D point cloud of the user via the Kinect sensor on the robot and extract a simplified model containing only points that likely correspond to the user's face. We do so by clicking on the image of the user's cheek, removing points more than 13 cm from the corresponding 3D clicked point, and creating a statistical color model in HSL color space from points within 3 cm of the clicked point. We then remove points $>$4.0 in Mahalanobis distance from the model in HSL color space. Finally, we manually position an ellipsoid (Sec. III below) with respect to this reduced point cloud model by visually adjusting the position, orientation, and l of the ellipsoid in rviz with interactive markers [21].

When running the system, the user seeds a new color model by clicking on his/her face in the video feed. Using the same method as above, the robot filters the point cloud for points corresponding to the skin of the person's head/face (Fig. 6A). Using the geometric shape of the saved point cloud model and the live model, the robot uses the iterative closest point (ICP) algorithm [23] to find their relative pose, and thus the desired correspondence between the saved, offline model and the user's head sensed by the robot's Kinect sensor.

The robot then provides a visualization of the model and its fit to the user's head on the live video feed. The user tells the robot if the registration succeeded (Fig. 6K). If unsuccessful, the user can repeat the procedure. This allows the user to localize his/her head with as few as three clicks: once on the 'Register Head' button to begin the process, once on his/her cheek in the live video feed, and once on the confirmation button. This is an improvement upon the method presented in [1] which required the use of a separate desktop application with a 3D interface.

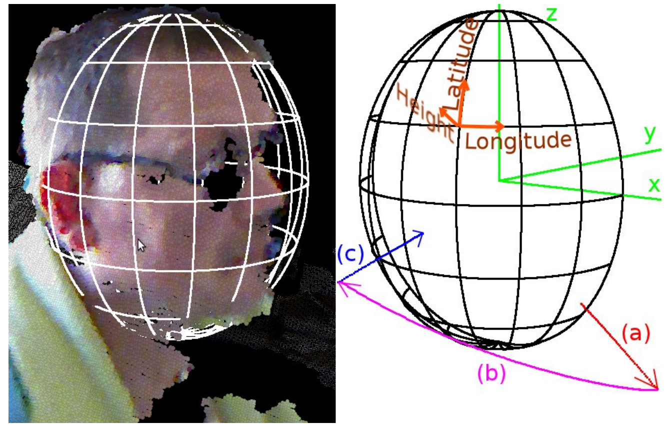

Fig. 5. **Ellipsoidal Model.** Left: A prolate ellipsoid fit to a point cloud of Henry's head. Right: The three paths illustrate a *global move* from the chin to the cheek. (a) retreats from the head, (b) moves around the head to the goal at a constant height, then (c) advances toward the face to the final goal position.

2) E-space Motion to Predefined Poses: Once the robot has a registered head model, and the user has moved the tool within 30-80 cm from his/her head (e.g., via trajectory playback), the interface provides controls for performing motions in E-space. Because the end effector can move slightly when initiating this subsystem, the 30 cm minimum distance ensures the tool is away from the user's head. The 80 cm maximum prevents use of the ellipsoidal controller when the robot's arms are still tucked in. We set both values heuristically.

The robot can make a *global movement* to one of many prerecorded, semantically-labeled locations around the head according to user commands from a drop-down menu of locations (Fig. 6F). The list of locations follows: "Cheek", "Corner of mouth", "Chin", "Front of neck", "Jaw", "Lip", "Near Ear", "Side of neck", and "Under chin." For each location, we record a tool pose in E-space by physically moving the tool to the desired pose during setup. We have developed tools to record, visualize, and edit these labeled poses.

The robot can perform a *global movement* from any tool pose near the head. The tool begins by moving from its location in E-space to a *retreat height* away from the user's head, which is a hand-tuned value of h in the E-space fit to a specific user. The latitude and longitude remain constant, and the orientation rotates to the canonical rotation with the tool pointing inward and orthogonal to the surface of an ellipsoid. The tool then moves across this ellipsoid, changing the latitude, longitude, and orientation to match those of the goal pose. Finally, the tool moves directly toward the user's head, reducing the height until the tool has reached the desired pose (Fig. 5). This results in tool trajectories that curve smoothly around the user's head. Larger values for the *retreat height* result in the tool moving along longer trajectories farther away from the user's head.

D. Finely Move the Tool via User Commands

While the *global move* capability can sometimes be sufficient on its own, other situations benefit from more precise

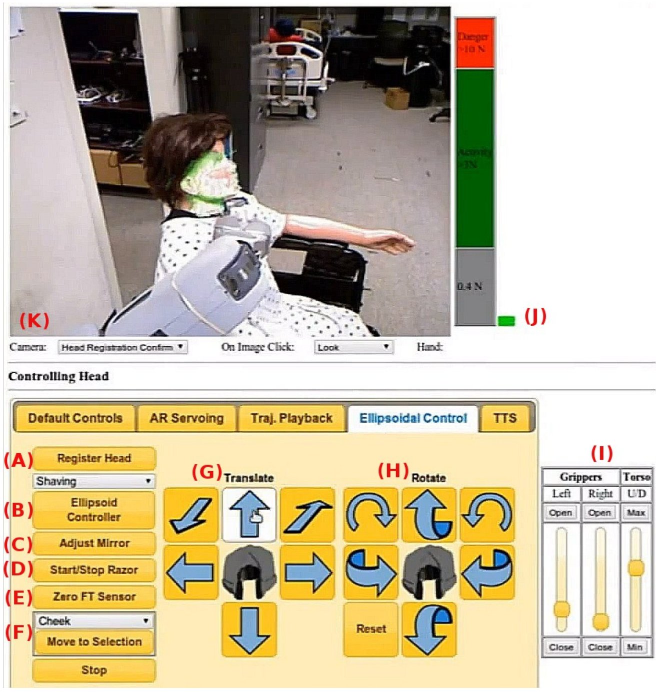

Fig. 6. **Ellipsoidal Control Interface:** (A) Begin head registration. (B) Activate ellipsoidal control. (C) Point mirror at head. (D) Toggle shaver power. (E) Re-zero force/torque reading. (F) Select head location for *global movement*. (G) Translate locally in E-space. (H) Rotate locally in E-space. (I) Control gripper and torso. (J) End-effector force display. (K) Live camera feed with registration confirmation overlay.

positioning of the tool. The robot uses E-space to guide local motions around the head. Users make local translations or rotations relative to the current location in E-space via 13 buttons (Fig. 6G,H). When the 'translate' buttons are pressed, the tool moves in E-space such that the latitude, longitude, or height coordinates change while the offset from the canonical orientation remains constant. This enables the user to move the tool around and toward/away from his/her head. The 'rotate' buttons rotate the tool relative to the canonical frame by fixed increments. The 'reset rotation' button returns the tool to the canonical orientation. The interface displays the buttons with a reference image of a tool in the center such that the arrows point in the directions the tool would move when viewed from the center of the E-space (i.e., from the user's perspective).

E. Hold the Tool While Monitoring and Reacting to Forces

An ATI Mini45 force-torque sensor [24] mounted at the wrist of the robot measures the forces at the end effector. The system monitors the estimated magnitude of the applied force at 100 Hz. Prior to computing this magnitude, the system subtracts out an estimate of the gravitational force due to the gripper and tool using a point-mass model.

Whenever the tool is moving (aside from during a *withdrawal*) and the measured force exceeds a contact threshold of 3N, the tool immediately stops. If the force exceeds a safety threshold of 10N the arm performs a *withdrawal*. As we reported in [3], we identified this 10N threshold by measuring and analyzing the forces used by able-bodied people to perform head-centric ADLs, including shaving. 10 N is slightly larger than the estimated maximum target force for all study participants who performed the shaving task. In a *withdrawal*, the latitude, longitude, and rotation are kept constant, and the tool is brought to a height away from the head, which is a hand-tuned value of h in the E-space fit to a specific user. If the tool is below a *neck safety threshold* latitude, the latitude is also moved up to the *neck safety threshold*, which is a hand-tuned value of ϕ in the E-space fit to a specific user. This keeps the tool from withdrawing directly toward the user's body.

When using tools such as an electric shaver, high forces can cause nicks and abrasions. For our system, this would most likely result from user error, since the robot holds the tool stationary while the user moves his/her head against it. A *withdrawal* attempts to alleviate this issue by breaking contact with the head when high forces occur, and also serves as a reminder to the user to limit the applied forces.

We originally implemented this capability due to nicks and abrasions Henry obtained during tests with our initial implementation, which did not monitor applied forces. We found that Henry was applying about 25N to himself by moving his head against the tool as it was held in a fixed position by the robot, while his wife and primary caregiver, Jane, only applied about 3N when assisting Henry with shaving. Unlike a human caregiver, the robot lacked common sense about appropriate forces for shaving and simply held the tool in place while Henry applied excessively high forces to himself. Since we implemented the force threshold triggered *withdrawal*, Henry has not experienced nicks or abrasions from using our system. He initially disliked the new *withdrawal* behavior, because he wanted to apply more force. However, he quickly learned to regulate the force he applied to himself in order to avoid unintentionally triggering a *withdrawal* while shaving. Interestingly, he would sometimes intentionally push against the tool to trigger a *withdrawal* and quickly move the arm away from him.

We found that due to inaccuracies in gravity compensation and drift in the force sensor, the estimated force magnitude at the end effector could be higher than the actual magnitude of the applied force. To help address this issue, the user has a 'rezero sensor' button that will *rezero* the force estimate. When pressed, the current force vector is used as an offset subtracted from subsequent measurements. The user is instructed to only use this function when the hand and tool are not in contact with anything.

Henry uses a head tracker and the screen in front of him to control the robot. The tool and arm can sometimes obstruct the head tracker and Henry's view of the interface, which can leave him unable to provide commands to the robot. To mitigate this issue, the robot monitors the user's activity, defined as either pushing one of the controller buttons or applying more than 3N of force to the tool, and performs a *withdrawal* after 30 seconds of inactivity.

(a) Robot away from user (b) After servoing approach (c) After arm untucking trajectory (d) During shaving task

Fig. 7. **Shaving Activity Sequence:** 7a): The robot starts away from the user. 7b: The robot reaches a pre-recorded pose relative to the wheelchair. 7c: The robot untucks its arms in preparation for shaving. 7d: The robot holds the tool at a user selected location.

F. The Web-based Interface

The user interface for the system is entirely web-based, using rosbridge [25] to communicate with the ROS software on the robot. This removes the need for the user to download or install software, and was useful during development since it allowed Henry to test the system remotely.

The interface provides visual feedback from the robot's cameras (Fig. 6K), text feedback from various subsystems, a colored bar showing the force on the one end-effector with a wrist-mounted force-torque sensor (Fig. 6J), and stateful slider controls for the grippers and torso (Fig. 6I). The user can direct the head camera by clicking directly on the live camera feed. The interface presents modal controls for each subsystem above. In addition, it provides a text-to-speech interface ('TTS') and a 'Default Controls' mode that enables the user to directly control the robot. With the 'Default Controls' the user can incrementally change the poses of the robot's head and end effectors with button clicks, and command the base to move with a constant linear or angular velocity by clicking and holding buttons. Sliders set the magnitudes of the incremental motions and the base velocities.

V. Evaluation

In this section, we report on a controlled trial with the system. During the trial, Henry shaved both sides of his face in his own home in California, USA. Prior to this trial, Henry had extensive experience using the PR2 to perform various tasks with other interfaces and research systems as part of the ongoing Robots for Humanity project. We conducted the trial during the fifth Robots for Humanity workshop on June 29, 2012. We consider Henry an expert PR2 user. Preceding the experiment, we gave Henry remote access to our system at the Healthcare Robotics Lab in Atlanta, Georgia USA. He remotely practiced using the system for approximately 12 total hours over two weeks before the workshop using a mannequin in a wheelchair. During this time, he provided feedback guiding our active development of the system. In one remote session on June 20, 2012, Henry successfully shaved a substantial part of the right side of Prof. Charles C. Kemp's face (Fig. 8). As Prof. Kemp is able-bodied, he attempted to hold his body still except for his head.

For in-person evaluation, we transported a PR2 robot to Henry's home and performed the necessary setup with Henry and his wheelchair. We attached ARTags on plastic boards to either side of Henry's wheelchair using zip ties. During the setup and evaluation, we placed the wheelchair with Henry in the middle of his living room, providing ample space for the robot on both sides. We recorded the navigation goal poses relative to his wheelchair and the initial arm trajectories, created a 3D point cloud model of Henry's head, fit an ellipsoid to this model, and recorded the semantically-labeled head locations with respect to E-space.

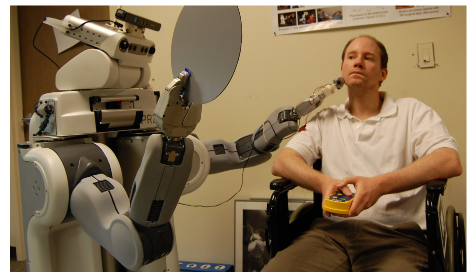

Fig. 8. Henry Evans tested the robot from his home in California by shaving part of the face of author Prof. Charles C. Kemp in Atlanta, GA.

The experiment consisted of a practice trial and an experimental trial. In the practice trial, a plastic cap was placed on the electric razor and Henry was instructed to go through the process of shaving his face until he was satisfied with completion of the task. As Henry had not shaved prior to the experiment, so that he would have facial hair for shaving, we wanted to preserve this for the experimental trial. We asked Henry to complete the task as quickly as possible while maintaining a comfortable pace, and to do so with as little experimenter assistance as possible. Since Henry is unable to speak, we instructed him to look at an experimenter and nod his head to confirm when he was satisfied performing the task. The instructions for the experimental trial were the same, but the cap was removed from the electric shaver.

At the start of the experimental trial the robot was 1.77 m from the front of Henry's wheelchair, with the arms in a tucked position not useful for servoing. For the entire experiment, the robot's torso was raised to its maximum height. The trial ended after Henry had moved the robot to both sides of his wheelchair, used the interface to shave, re-tucked the arms, and backed the robot safely away. Immediately following the experimental trial, Henry filled out a questionnaire with 7 point Likert items regarding his experience where 1="Strongly Disagree," 4="Neutral," and 7="Strongly Agree." The appendix at the end of this

Fig. 9. The top row shows Henry's face before the shaving trial. The bottom row shows Henry's face after the shaving trial.

paper provides the questions and Henry's responses. He also completed an unweighted NASA Task Load Index (TLX) questionnaire to assess the amount of workload experienced during the task according to six 21-point sub-scales. These sub-scales measured mental, physical, and temporal demand as well as performance, effort, and frustration [26], [27]. We categorized scores ranging from 1-7 as "Low," 8-14 as "Medium," and 15-21 as "High" for all sub-scales except performance, where "Low" and "High" categories were switched, since performance was an inverse scale.

VI. Results

A. *Objective Results*

Henry was able to use the robot to shave his left and right cheeks, chin, neck, and upper lip (Fig. 9). Henry successfully navigated the robot to both sides of his wheelchair and completed the trial when he backed the robot away from his wheelchair, completing the full task in 54 minutes.

During the trial, there were three stops due to system failure. The first failure was caused by a loss of network communication with the robot's computers, including from the interface computer, requiring a system reset. The second was a motor signal timeout, a safety routine in the PR2's realtime controllers which deactivates the motors if there are delays in communication between motors and control system. These two stops were hardware failures due to this being a proof-of-concept research system and do not directly pertain to our results.

The third pause was an experimenter-initiated stop, occurring very shortly after the second hardware failure. Henry unnecessarily played the trajectory that initially configures the tool-holding arm a second time. Due to our joint-space interpolation method which brings the arm to the joint configuration at the start of a recorded trajectory, the robot's arm would have moved into Henry's arm if the experimenter had not stopped the robot. Unlike the other two stops, this stop reflects usability issues with our current implementation.

All three of these stops occurred while the robot was on Henry's right side. After the third stop, Henry was able to navigate the robot to his left side and shave his left cheek without any additional stops.

B. *Subjective Results*

Henry had both positive and negative reflections on the system. He strongly agreed (Likert-item score (L.I.S.) of 7) that the system was comfortable and enjoyable to use, and that he felt safe during the experiment. He agreed (L.I.S. 6) that he was satisfied using the system to complete the shaving task, and that he would prefer to use the system to perform the task as opposed to asking a caregiver.

Henry slightly agreed (L.I.S. 5) that he could effectively use the system to complete the task. However, he slightly disagreed (L.I.S. 3) that he was satisfied with the time it took to complete the task and that the system was easy and intuitive to use. Furthermore, he disagreed (L.I.S. 2) that the web interface layout and icons were intuitive.

The unweighted NASA TLX sub-scale scores supported Henry's report of high mental demand and effort (scores of 17 and 15, respectively), medium performance (13), and low frustration, low physical demand, and low temporal demand (4, 5, and 5, respectively). In a followup questionnaire, Henry reported that he would prefer a step-by-step "wizard-like" process as opposed to a set of distinct tools.

VII. Discussion and Future Work

With this system, Henry was able to bring the electric shaver to most locations on his face. Figure 9 shows that he was able to shave many of these areas. The quality of the shave varied across the face, with a relatively good shave on his cheeks, while the most substantially unshaven location was underneath his chin on his left side.

Why the shave was of lower quality in some locations is an open question. Additional time shaving may have resulted in a more uniform and higher-quality shave. The long time required and high mental workload associated with the activity may discourage users from continuing. This may warrant further investigation into more autonomous contact behaviors, such as having the robot actively move the tool across a person's face. It is also possible that the mirror and lighting did not provide adequate visual feedback. For example, the mirror was farther from Henry's face ($\approx 1m$) than is typical when an able-bodied person shaves his face, and the lighting in the living room lacked the qualities associated with bathroom lighting, such as brightness and direction. Additionally, Henry's facial hair was relatively long (a few day's growth), requiring more time to shave fully. Henry also reported that it was uncomfortable for him to move his neck enough to shave his neck effectively.

The time required to shave could potentially be achieved with a variety of practical improvements. Many of the robot's movements could be sped up, which Henry indicated would be desirable. Also, semi-autonomous navigation instead of manual driving to move the base around the wheelchair might be more efficient. Most importantly, enabling the robot to reach both sides of the head from one side of the body would significantly reduce operating time and complexity, and reduce the space required to use the system, although this would most likely require changes to the hardware, if not a different mobile manipulator altogether.

During both remote testing and the experimental trial, Henry had difficulty using the trajectory playback subsystem effectively. Occasionally, he would play a trajectory when the arm was far from the initial configuration associated with the trajectory, and the arm would attempt to move through his body (e.g., before the experimenter-initiated stop during the trial). This aspect of the system should be improved, such as by checking if the current arm configuration is close to the initial arm configuration for the trajectory or checking for potential collisions prior to execution of the trajectory.

Henry's feedback suggests that he liked using the system, but felt that the design could be more user-friendly. How an "interactive wizard" approach would compare with a "Photoshop-like" panel of tools remains an open question, and each may have advantages in different contexts. Providing access to a collection of lower-level tools may make the system more versatile and enable the user to overcome failures due to unexpected situations. Providing a higher-level interface may improve the ease of use and reduce workload. A system that has both levels of interface available to the user, with the more complex controls hidden unless specifically requested, might be feasible and appropriate.

Since each subsystem requires practice and understanding to execute properly, and complete task performance requires understanding how to use the subsystems together, our system is likely a better match for expert users like Henry. We would expect assistive mobile manipulators to eventually serve as personal assistive devices for daily use over months to years. This might result in expert users who are willing to use more complex interfaces. Nonetheless, interfaces for novices are an important direction for future research, since they would have clear benefits, such as encouraging adoption of this assistive technology.

We designed our system with the expectation that it could be used for multiple ADL's around the head. Other tasks around the face could potentially use the same setup data other than the task-specific force thresholds. Tasks involving reaching the rest of the head would likely require distinct setup data. Currently, the system relies on a setup procedure for each user and wheelchair. Making this initial setup more efficient and generalizing capabilities across users, potentially through greater robot intelligence, would be interesting areas for future inquiry.

VIII. Conclusions

Our proof-of-concept system demonstrates that a general purpose human-scale mobile manipulator can enable a person with severe motor impairments to shave himself in his home, a task that he would otherwise not be able to perform. Distinctive characteristics of our system include user-supervised navigation of the robot to the wheelchair, user-guided registration of a 3D head model, coarse tool positioning to semantically-labeled poses, an ellipsoidal coordinate system for tool motions around the user's head, and force monitoring to trigger a withdrawal. Our system provides a number of examples of how the complementary capabilities of a mobile manipulator and a human user with disabilities can be brought together to empower the human user.

IX. Acknowledgments

This work was supported in part by Willow Garage, NSF awards IIS-1150157 & CNS-0958545, and NIDRR Grant H133E130037 as part of the TechSAge RERC. We thank all the members of the Robots for Humanity project for their help with this work. We also give special thanks to Henry Evans, Jane Evans, and Steve Cousins.

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X. Appendix

Table I lists the Likert Items and Henry's responses after using the system. Possible responses were 1: Strongly Disagree, 2: Disagree, 3: Slightly Disagree, 4: Neutral, 5: Slightly Agree, 6: Agree, and 7: Strongly Agree. Table II lists the non-Likert Item questions and Henry's responses after using the system.

Likert Items	**Responses**
It was easy to use the default controls to drive the robot to a position where it could view the AR tag.	7
I could effectively use the default controls to drive the robot to a position where it could view the AR tag.	7
It was easy to use the AR servoing approach controls to command the robot to autonomously drive to my wheelchair.	7
I could effectively use the AR servoing approach controls to command the robot to autonomously drive to my wheelchair.	7
I felt safe when the robot was moving toward my wheelchair.	7
It was easy to use the head registration system to register my head.	7
I could effectively use the head registration system to register my head.	5
It was easy to use the trajectory playback tools to setup the robots arms to position the mirror and shaver.	5
I could effectively use the trajectory playback tools to setup the robots arms to position the mirror and shaver.	3
I felt safe while using the trajectory playback tools to setup the robots arms to position the mirror and shaver.	7
It was easy to use the dropdown menu to position the shaver at different poses around my face.	7
I could effectively use the dropdown menu to position the shaver at different poses around my face.	2
I felt safe using the dropdown menu to position the shaver at different poses around my face.	7
Using the dropdown menu to position the shaver at different poses around my face was intuitive.	5
It was easy to use the local ellipsoidal controller to position the shaver at different poses around my face.	4
I could effectively use the local ellipsoidal controller to position the shaver at different poses around my face.	2
I felt safe using the local ellipsoidal controller to position the shaver at different poses around my face.	7
Using the local ellipsoidal controller to position the shaver at different poses around my face was intuitive.	2
I could comfortably move my head to reach the parts of the face I wanted in order to complete the task.	3
I could easily move my head to reach the parts of the face I wanted in order to complete the task.	2
I could effectively move my head to reach the parts of the face I wanted in order to complete the task.	1
I was able to apply enough force to my face in order to complete task.	7
I felt safe when I was moving my face against the shaver to perform the task.	7
The web interface layout was intuitive.	2
The web interface icons were intuitive.	2
I was satisfied with the responsiveness of the web interface (not the responsiveness of the robot moving).	6

TABLE I

Non-Likert Questions	**Responses**
Approximately many times did you re-register your head because the registration process failed?	4
Approximately many times did you re-register your head because you wanted to move your head to a different neutral position?	0
Did you use the dropdown menu to move the shaver to a pre-specified pose around your face?	Yes
With regard to the speed the shaver moves using the local ellipsoidal controller, I would prefer that the shaver moves:	Somewhat faster
With regard to the speed the shaver moves using the dropdown menu, I would prefer that the shaver moves:	Much faster
With regard to the distance the shaver moves with each button press using the local ellipsoidal controller, I would prefer that the shaver moves:	Much further
Did you use the local ellpisoidal controller to position the shaver at different poses around your face?	Yes
Which location on your face was the most difficult to shave?	Side of Neck
Which location on your face was the easiest to shave?	Chin

TABLE II