

LASER ASSISTED COMBINED TELEOPERATION AND AUTONOMOUS CONTROL

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ABSTRACT

In this paper we demonstrate combined human teleoperation and autonomous control of a remote manipulator in an unstructured environment to enable people with limited upper body strength to carry out a remote task. Range data from a laser sensor mounted on the end-effector of a remote manipulator is used by the user to select via-points in teleoperation. This information enables autonomous execution of trajectories. The human user is primarily involved in higher level decision making; the user performs minimal teleoperation by selecting critical points using a laser. In the event the sensor or human detects an unexpected obstacle during autonomous trajectory execution, the controller terminates the trajectory so that the human can teleoperate the end-effector safely around the obstacle. Once the obstacle has been averted, the system resumes the control and guides the manipulator autonomously to the target. Tests on healthy human subjects on a pick-and-place task involving multiple objects showed that this combined teleoperation and autonomous methodology using minimal sensory data made it physically and cognitively easier for the user to execute the task.

Key Words: Teleoperation, Telerobotics, Sensor, Human Robot Interaction

1 INTRODUCTION

According to the 2006 US Census Bureau report [1] 51.2 million Americans suffer from some form of disability and 10.7 million of them are unable to independently perform activities of daily living (ADL). They need personal assistance to do ADLs such as to pick-and-place an object or open a door. Robotic devices have been used to enable physically disabled individuals to execute ADLs [2]. However, teleoperation of a remote manipulator puts a lot of physical and cognitive load on the operator [2], more so for persons with disabilities. There have been previous attempts to provide computer based assistance by combining teleoperation and autonomous modes in shared and traded control formulations [3] [4] [5], by means of virtual fixtures [6] and potential fields [7]. Previous work at the Rehabilitation Robotics Laboratory at the University of South Florida has focused on reducing operator's fatigue by providing assistance depending on the accuracy of sensor and model information [8], augmenting the performance of motion-impaired users in job-related tasks using scaled teleoperation and haptics [9], and providing assistance based on real-time environmental information and user intention [10]. Our recent work [11] demonstrated the use of a laser sensor in identifying target objects, obstacles and goal points by human in teleoperation. This information enabled autonomous execution of trajectories under human supervisory control. The methodology resulted in an increased speed of task execution. It also reduced the physical effort in executing the task by 85.4%.

In this work, we have considered a more general testing environment and the possibility of encountering unexpected obstacles while executing a remote task. The human in teleoperation scans the environment for critical points using the laser. The coordinate of each point is recorded using arm kinematics and laser range data. Here the critical points are the via-points for the remote arm trajectories. In a pick-and-place task, these could be the points from where objects are picked up and dropped. Once the points are recorded, the arm autonomously executes the trajectories between these via-points. In case an unexpected obstacle is encountered, the human terminates the trajectory and steers the arm clear of the obstacle. The obstacle can be detected by the laser sensor as long as it is in the line of sight of the laser. In this case also the human steers the arm clear of the obstacle. After that the system autonomously guides the arm to the via-point where the arm was headed before the obstacle detection.

Thus the human user is involved in making high level decisions and minimal teleoperation during the task execution. The system manages the low level execution. We hypothesize that this combined teleoperation and autonomous mode of task execution using laser based assistance will make it easier for human users to execute remote tasks. The proposed methodology is intended for use by persons with disabilities in executing ADL tasks. However, the methodology has a much broader scope for implementation and could be used in telerobotics based application areas like nuclear waste clean-up, robotic assisted surgery, space/under-sea telerobotics etc.

2 RELATED WORK

Hasegawa et al. [12] enabled autonomous execution of tasks by generating 3D models of objects with a laser sensor that computed 3D coordinates of points on objects. These models were compared to a database of CAD models to match objects. Takahashi and Yashige [13] presented a simple and easy to use laser-based robot positioning system to assist the elderly in doing daily pick-and-place activities. The robot in this case was an x-y-z linearly actuated mechanism mounted on the ceiling. Nguyen et al. [14] made use of a system consisting of a laser pointer, a monochrome camera, a color filter and a stereo camera pair to estimate the 3D coordinates of a point in the environment so their robot could fetch objects in the environment designated with the laser pointer. Here we use the laser range finder to select via-points that enable autonomous execution of trajectories under human supervisory control.

3 LASER ASSISTED CONTROL CONCEPT

To execute a remote task, the human user teleoperates a PUMA manipulator via a Phantom Omni haptic device. To make teleoperation easier, we have implemented Cartesian based mapping from the Omni coordinate frame to the PUMA coordinate frame. As the Omni is teleoperated by the human user, incremental end-effector transformation matrices from the Omni are sent to the PUMA controller at a rate of 1000 Hz. Differential velocity components from these transformation matrices are then computed. These are mapped to the PUMA coordinate system using the equation (1). This aligns the two coordinate frames thus producing motion on the PUMA similar to that on Omni. This makes teleoperating the PUMA intuitive to the user.

$$Vel_{PUMA} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} * Vel_{Omni} \quad (1)$$

The laser is mounted on a bracket on the end-effector as shown in Fig 1. The laser beam is always parallel to the z-axis of the end-effector. By teleoperating the end-effector the user is easily able to point to different points in the environment. Using the range information of the laser sensor and the PUMA kinematics, the user is able to record the 3D coordinates of the points the laser is pointing to. This information is used by the system to generate the start and the end points of the trajectories and the equations of the surface normals.

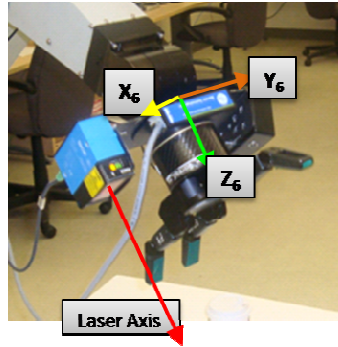


Figure 1. Laser sensor mounted on the end-effector

3.1 Laser based Target Point Determination and Autonomous Trajectory Execution

For generating a linear trajectory, the coordinates of the start and the end points are needed. From Fig. 2, we see that as the laser points to ‘Target’, the system determines the coordinates of this point using the transformation equations given in Equation (2).

$$T_O^B = T_E^B * T_L^E * T_O^L \quad (2)$$

where O, L, E and B stand for object, laser, end-effector and base respectively. Each term in the equation is a 4x4 homogenous transformation matrix. T_E^B is known from forward kinematics. T_L^E has a unit rotation matrix part and its translation components are the offset distances of the laser point source from the end-effector or from joint 6. T_O^L has a unit rotation matrix part and its translation components are [0 0 D], where D is the distance measured by the laser.

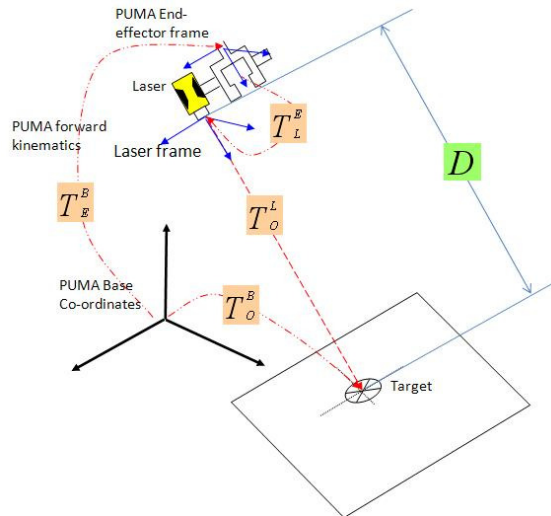


Figure 2. Concept – Recording a point using laser range finder

After the start and end points are recorded, the trajectory points are generated using linear interpolation and the equivalent angle-axis method. These trajectory points are stored in an array and read at a rate of 200 Hz. Joint angles from these are determined using Resolved Rate algorithm. Then using a PD control law, joint torques are computed and the trajectory is autonomously generated.

3.2 Laser based Autonomous Surface Alignment

Surface alignment of the end-effector is essential to grasp an object from a convenient angle. This is implemented as an autonomous function. For surface alignment, it is necessary to determine the equation of the surface normal. By pointing to three points on a surface using the laser, their coordinates are recorded as mentioned in the previous section. Let the points be denoted by P_1 , P_2 and P_3 (refer Fig. 3). Let \vec{A} and \vec{B} be the vectors connecting the three points as shown in the figure. The surface normal is then computed as $\vec{A} \times \vec{B}$. The negative of the surface normal will be the end-effector z-axis after it has aligned with the surface. The x and y-axes are computed using criteria for minimum end-effector rotation. For this, the cross product of the x-axis (before alignment) with the z-axis computed above gives the y-axis. The cross product of the y-axis with the z-axis gives the x-axis. The x, y and z-axes thus computed become the columns of the rotation matrix of the end-effector after it has aligned with the surface. Equivalent angle-axis method is used to determine the trajectory points for autonomous rotation.

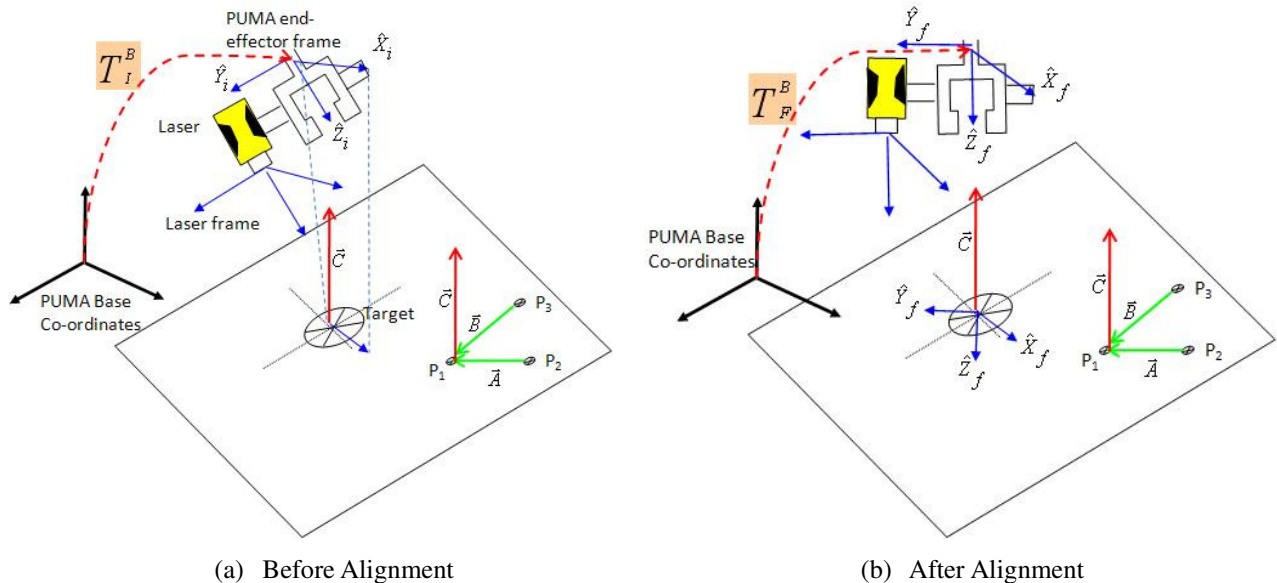


Figure 3. Concept – Laser based autonomous surface orientation by recording three surface points

4 APPLICATION OF LASER BASED CONCEPT TO TASK EXECUTION

Here we give an example of a pick-and-place task with unexpected obstacles and demonstrate how the laser based assistance functions are used to execute the task. During the task, the user commands the system to carry out specific actions using specific keyboard keys.

Fig. 4 shows the various steps during the execution of a pick-and-place task using a laser. The user starts executing the task by pointing the laser to three points on a surface and recording the coordinates of each point by pressing a keyboard key (Fig. 4(a)). The surface in this case is any platform where an object is placed or needs to be placed. These three points will enable autonomous surface orientation later that helps to align the end-effector with the surface. This will enable grasping or placement of the object from/on the surface from a convenient angle thus making it easy. Next, the user points to the various via-points in the pick-and-place task (Fig. 4(b), 4(c), 4(d)). The user then commands the system to execute autonomous trajectory to the first via-point recorded (Fig 4(e)). At any point, if necessary, the user can command the end-effector to autonomously align with the surface by pressing the required keyboard keys. After picking up object 1, the user commands the system to autonomously go to the second via point (Fig. 4(f)). If the user encounters an unexpected obstacle, the user commands the termination of the trajectory. The user then steers the arm clear of the obstacle (Fig. 4(g)). After this, on user command, the system autonomously generates a trajectory to go to the second via-point where it was supposed to go before the obstacle was detected (Fig. 4(h)). Object 1 is dropped at the second point. The user then commands the system to autonomously go to the third via point to pick up object 2.

At times, certain points in the environment are difficult to point to with the laser due to the arm joint limits and the extended bracket for mounting the laser. The extended bracket makes it difficult to orient the end-effector beyond a certain limit. In such cases, the user can point to these points when the end effector is near them. In the set-up shown, the user needs to drop off object 2 to the target location. The user selects the point and commands the arm to autonomously go to that point (Fig. 4(i)). If an unexpected obstacle appears in the path of the laser, the laser detects it and the trajectory is terminated by the system (Fig. 4(j)). An object is considered as an obstacle if it is within a certain threshold distance of the laser. After the user steers the arm clear of the obstacle (Fig. 4(k)), the user commands the arm to go to the point it was previously supposed to go, in this case the drop-off point for object 2. The system generates and executes an autonomous trajectory in this case too (Fig. 4(l)).

Thus the user supervises the task and generates high level commands while the system generates and executes trajectories. The only phases of the task where the user teleoperates is during the selection of via-points, surface points, steering the arm clear of obstacles and fine adjustments to locate the end-effector for convenient grasping. In this way the user does minimal teleoperation while executing the task. This results in fewer movements by the user to execute the task. Also, once the points are recorded, the user need not bother about locating the points again. The system autonomously steers the arm to the target location even if unexpected obstacles appear. This provides further assistance.

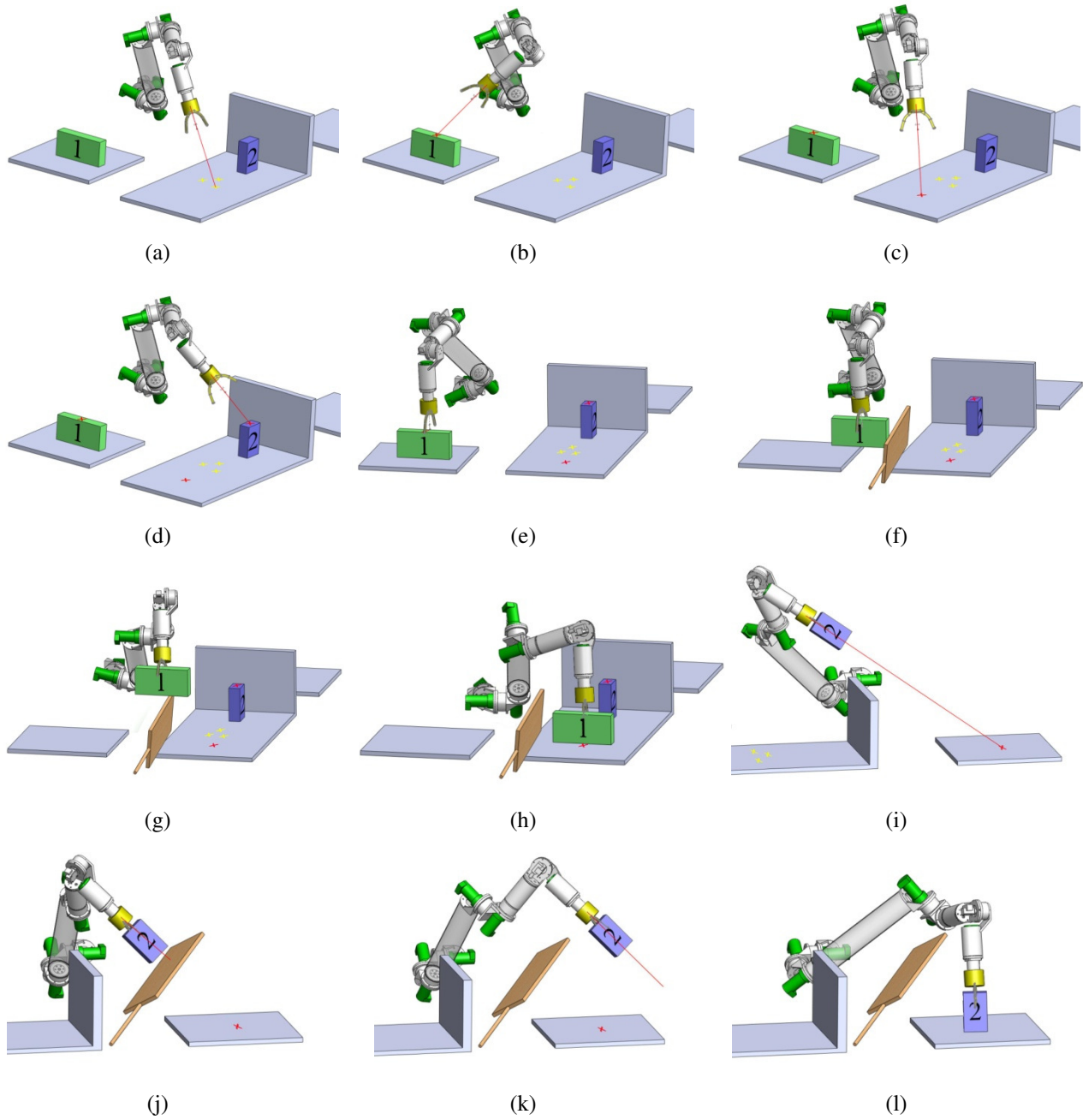


Figure 4. Steps in laser based pick-and-place task execution

5 EVALUTATION OF THE EFFECTIVENESS OF LASER BASED METHOD

5.1 Experimental Test Bed

Our test bed consists of a PUMA arm and an Omni haptic device (Fig. 5). A SICK DT60 laser range finder is mounted on the PUMA end effector (refer Fig.1). The subjects could see the remote environment directly as the PUMA and Omni were close to each other. For applications in which the remote environment is further away, cameras can provide visual feedback. The PUMA and Omni were controlled on separate PCs communicating via Ethernet. The communication between PCs and data processing was at 1000 Hz. A real-time operating system, QNX, with a multithreaded programming architecture was used to control the PUMA. The Omni was controlled on Microsoft Visual C++ on a Windows machine.



Figure 5. PUMA and Omni manipulators

5.2 Experimental Methodology and Set-up

In order to evaluate the effectiveness of the laser-assisted method, human subject testing was carried out. Although the laser-based method is intended for assisting people with disabilities to perform ADLs, here we have tested healthy human subjects. We tested five subjects, all males, ages 22 to 40 years. None of the subjects had any experience in using manipulators.

Each subject was asked to perform a pick-and-place task three times in each of the two modes: the unassisted teleoperation mode and the laser-assisted mode. In the unassisted mode, the complete task was executed solely by teleoperating the PUMA without any assistance. For each run the time taken to complete the task and the end effector transformation matrix was recorded at 1 millisecond intervals. The user experience in executing the task was also recorded for each user. Before starting the tests, the subjects were given sufficient time to acclimatize with the system. In general, each subject was given 5 to 6 trials before testing.

The experimental set up is shown in Fig. 6. The three via-points are the box on the stool on the left, the green sticky on the shelf to its right and the yellow box. The green sticky on the far right of the shelf is not considered a via-point because it is out of the range of safe PUMA end-effector orientation from its initial or Ready configuration (the PUMA configuration shown in Fig. 6 is not the initial or Ready configuration). This last point is recorded by the laser after the yellow box has been picked up whereas the three via-points are recorded at the very beginning of the task execution when the PUMA is at Ready configuration. The task in each mode is to start from the Ready position, pick up the white box and place it at the second via-point, pick up the yellow box and place it on the green sticky on the far right. If an unexpected obstacle appears, then it has to be detected by the laser if the obstacle is within its line of sight, otherwise it should be detected by the human. Accordingly, the trajectory is terminated by the system or by the human. The obstacle has then to be averted in teleoperation. Next the user continues

teleoperating or commands the system to generate a trajectory autonomously. This depends on whether the mode is unassisted or laser assisted.

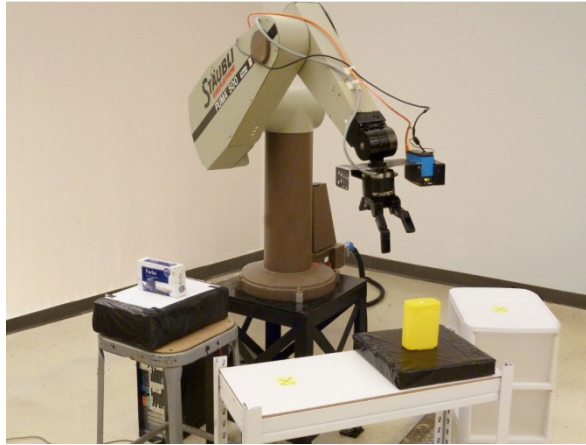


Figure 6. Experimental set-up for pick-and-place task execution

6 RESULTS AND DISCUSSIONS

The time that each user takes to execute the task in each mode and the amount of hand and arm motion utilized in doing the task, are the metrics used to evaluate the laser-assisted control method. The user experience was also recorded after each participant completed their test trials.

The average time to complete the task is shown in Fig. 7. We found that subjects took an average of 56.14% more time to complete the task in the laser-assisted mode than they did in the unassisted mode. Therefore no savings in time was observed with laser-assisted mode. However a major portion of the time in the laser-assisted mode was used in setting up the task by pointing to the via-points and surface points. Also due to the joint limits of the PUMA and the extension of the bracket on which the laser sensor and camera is mounted (Fig. 6), it is difficult to point to certain points in the environment. Teleoperation is needed in these cases to get the arm at a convenient configuration to point. These issues delay the task execution in laser-assisted mode. If the task demands that these recorded points are to be used again in the future, then the laser-assisted mode should be faster. This will also be possible if the range of motion of each joint is increased, joint limit avoidance is implemented or the bracket design mounts the laser closer to the end-effector.

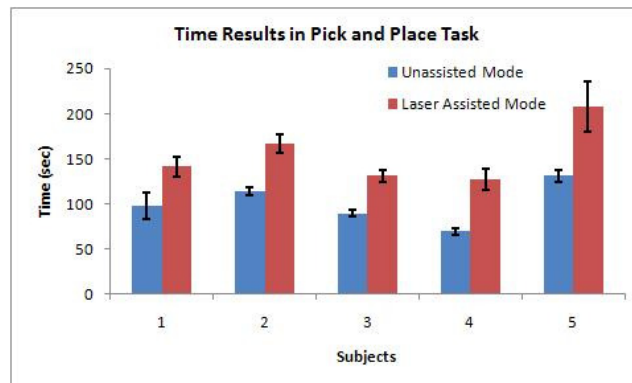


Figure 7. Time to execute the task in the laser assisted and unassisted modes

The amount of motion of the user’s hands and arms in executing the task was measured as they teleoperated the Omni in each of the two modes. The movement was broken up into distance traversed by the arm and rotation of the wrist. Total distance traversed by a subject's arm was determined by summing up the differential translation components of the Omni transformation matrices recorded at each time step during task execution. The total angle rotated by the subject’s wrist during task execution was also determined by applying the equivalent angle-axis method to the differential rotation components of the transformation matrices recorded at the Omni. Average values of arm distances and wrist angles per subject per mode for the three trials are shown in Fig. 8 and Fig. 9.

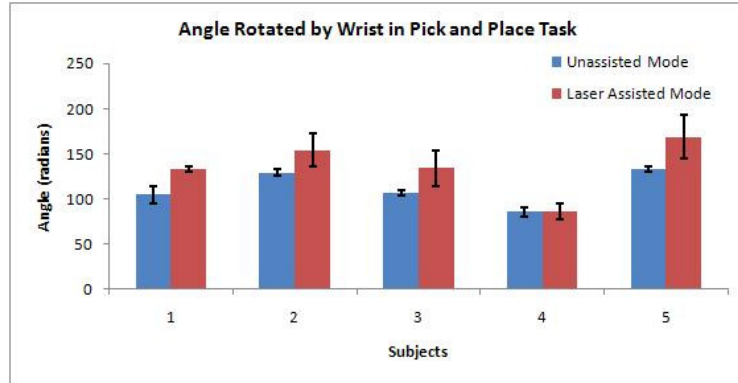


Figure 8. Average total angle rotated by users’ wrist while teleoperating in the two modes

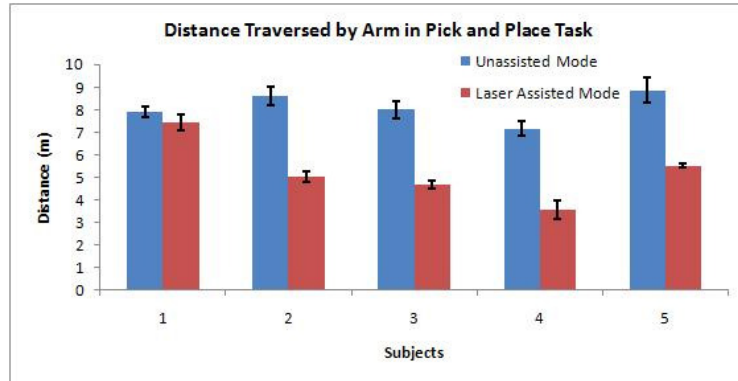


Figure 9. Average total distance traversed by users’ arm while teleoperating in the two modes

From these plots, we see that the subjects’ make larger movements with their arms while executing the task in unassisted mode than they do in the laser-assisted mode. On average over all trials for all participants, the arm movements were 35% less in the laser-assisted mode. However, the wrist movements are an average of 20% more in the laser-assisted mode. The increase in the wrist movements can be attributed to the initial rotation that the user engages in while selecting via points. Moreover, overcoming the obstacle is carried out in teleoperation in either of the two modes which results in considerable amount of wrist rotations. The decrease in arm movements in the laser-assisted mode is due to the users not needing to teleoperate between via-points. Autonomous trajectories are generated for this purpose. This result is of special significance since the system is intended for use by persons with disability. Less arm movements would make the task easier for them to perform.

At the end of their test trials, the users were asked about their experience in executing the task in the two modes. The users were of the opinion that the laser-based method was much easier since they did not have to execute the trajectories; the system did it for them. All the participants felt that pressing the various keyboard keys for recording surface points, via-points, trajectory termination, trajectory execution etc. was tedious and remembering them was a burden. They believed that the laser-based method would have been easier if there was a better interface or if they had to make fewer key presses.

7 CONCLUSIONS

Thus, we have demonstrated an easy-to-use interface using the laser sensor to execute remote tasks. Although it took longer for the able-bodied test subjects to execute the task in the laser-assisted mode, they made significantly less arm movements. This is very important for people with disabilities since their main aim is to execute the task; speed of task execution does not matter as much to them. As part of future work, we would like to make the interface easier to use by either using voice control or reducing the number of key presses for enabling features. We intend to make the teleoperation easier by incorporating joint limit avoidances and singularity avoidances. We would like to test visual feedback based teleoperation since at times it is impossible for the user to see where the laser is pointing due to distance or occlusion. Autonomous obstacle avoidance and autonomous end-effector orientation by human motion intention recognition would reduce teleoperation further. These areas will be explored in the future.

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