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Task-Oriented Control of a 9-DoF WMRA System for Opening a Spring-Loaded Door Task

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***Abstract*— A 9-Dof wheelchair mounted robotic arm system (WMRA) has been developed to assist wheelchair-bound persons with upper limb motion limitations to perform activities of daily living (ADL) tasks. In this paper, we utilize mobile manipulation control to keep the end-effector stationary while moving the base and vice versa. This allows easier execution of a group of pre-set ADL tasks including opening and holding a spring loaded door passing through by locking the end-effector position and orientation. Redundancy resolution is achieved by optimizing the manipulability measure while the ADL task is being performed. Combined mobility and manipulation is expanded in this work to turn the USF WMRA into a task-oriented robotic system.**

Index Terms - ***Task-Oriented, Mobile Robot, Manipulator, Redundancy, ADL***

I. INTRODUCTION

A wheelchair mounted robotic arm (WMRA) has been designed and developed to aid persons in a wheelchair with limited upper mobility to help then perform activities of daily living. The USF WMRA consists of an articulated 7 degree of freedom arm attached to a power wheelchair, which is considered to be a 2 DoF non-holonomic base. The 9 DoF freedom system has 3 degrees of kinematic redundancy. This challenges the control of the system for combined mobility and manipulation, but provides room for optimization for different sub-tasks, such as singularity and obstacle avoidance.

Previous work presents the resolved rate control algorithm of the 9 DoF WMRA showcasing different modes of operation, user interfaces and types of optimization [7]. Redundancy optimization was also implemented to control 2 separate trajectories in the WMRA system; a primary trajectory for the end-effector, and an optimized secondary trajectory for the wheelchair. This work was illustrated in the completion of a "go to and open the door" task, which demonstrated the performance of the algorithm.

This work expands on the concept of separate trajectories for the end effector and the mobile base of a mobile manipulator for its relevance in rehabilitation robotics applications. For instance, completing the task of going through a spring loaded door once it has being opened by the WMRA presents a new challenge, which is to control the orientation and pose of the end-effector holding the door knob or the door while the mobile base passes through the door. The relevance on this work is evidenced in the control of these separate trajectories within a single control scheme; thus allowing many pre-set ADL tasks to be executed by the 9 DoF WMRA, turning it into a task-oriented mobility and manipulation system.

II. BACKGROUND

Task execution in mobile manipulators presents the challenge of controlling the manipulator and the base, while allowing for non-holonomic constrains. In [1] a 7 DoF mobile manipulator consisting of a 5 DoF arm mounted on a 2 DoF wheeled platform was controlled by coordinating the platform motion and the gripper motion. The platform is driven to a destination that put the target within the gripper's workspace, and then it performs the given task with the manipulator.

Oriolo et.al have recently presented their work in the field of control of non-holonomic manipulators, task related programming and motion planning for specific end effector configurations [2], [3], [4]. In [2] they consider the problem of planning the motion of a redundant mobile manipulator to avoid obstacles when given a specific path for the end-effector. This work takes into account the non-holonomic nature of the base at the planning stage. This shows great promise for task performance, but given that our application is to aid persons with disabilities, we need to take special care of the wheelchair motion when achieving a certain task. In [3] they extended their approach to include task space constraints when following a specified path with the end-effector. This builds on the capacity of the algorithm to take advantage of redundancy to avoid obstacles.

When it comes to the task of opening doors, recent work has been made in this area showing very good results pushing doors open and opening standard doors [5], [6]. In [5] they use passive mode joints to provide compliance in the task allowing the joints to rotate freely with friction compensation. This mode is also used as a method to calculate the radius of the door. A shift into advanced sensor implementation was presented in [6]. Here they implement a method to push doors open and autonomously plug their robot in case that it needs to recharge its batteries. They do not focus on doors that open towards the user or concentrate in the base motion or collision. It is a very robust algorithm for motion planning and it showcases the intelligence of their robot.

Our previous work [7] presented an optimized dual-trajectory-following control for our 9-DoF WMRA system. A secondary trajectory for the wheelchair to follow was mathematically represented and implemented for a "Go To and Open the Door" task. Joint limits for the manipulator joint variables and the position/orientation variables for the wheelchair were used in the weight matrix to prioritize or penalize the motion of the nine control variables. In [10] a task-oriented procedure was also proposed to design a robotic arm to perform pre-defined tasks. They formulated several pre-set tasks based on observation of person with disabilities in order to program their robotic system accordingly. This provides a base to program robotic task-oriented robotic systems such as our 9 DoF WMRA to perform ADL tasks.

III. MOTION PLANNING AND CONTROL

3.1 Task Problem Definition

Our previous work in [7] opened up a door into optimized task performance by optimizing the wheelchair orientation while following a main trajectory with the end effector. A new problem arises when it is needed to pass through this door. As noted in the previous section, great work has been recently presented in pushing doors open and opening doors towards the user and then let them go to proceed with the next planned motion. This work intends to solve the problem of going through a spring loaded door that opens towards the user. This task is broken down into these main steps:

- Hold the door knob and move the arm and wheelchair to open the door [7].
- Hold the door know while the wheelchair moves forward enough to release the door without problem.
- Get the arm in front of the door to push it and keep it open.
- Proceed going through the doorway.
- Release the door and continue moving away from the door

These steps each bring different mobility and manipulation problems to be solved. The first step is achieved by the dual-trajectory control scheme presented in [7].The most complex, and the main contribution of this paper, is presented in the second step. Redundancy must be resolved to allow the wheelchair motion while maintaining the end effector locked in position and orientation. The third step will consist of generating a trajectory for the arm to get in front of the door while the wheelchair remains in place blocking the door from closing, and the fourth step will be to push the door while the wheelchair moves through, which will be a second implementation of the solution that was obtained for the second step. For the last step the door will be released and the wheelchair will continue moving through the doorway. By successfully implementing the combined control of mobility and manipulation for this complex task will allow further implementation of this algorithm for many simpler, but also needed, activities of daily living task, aiming towards a task oriented mobile manipulator.

3.2 WMRA Combined Kinematics

Two of the DoFs are provided by the non-holonomic motion of the wheelchair. This subsystem is controlled using 2 input variables: the linear position of the wheelchair along its x-axis, and the angular position of the wheelchair about its z-axis (see figure 1). The planar motion of the wheelchair includes three variables: the x and y positions, and the z-orientation of the wheelchair [13].

The differential drive used in power wheelchairs represents a 2-DoF system that moves in plane. Assuming that the manipulator is mounted on the wheelchair with L2 and L3 offset distances from the center of the differential drive across the x and y coordinates respectively, the mapping of the wheels' velocities to the manipulator base velocities along its coordinates is defined by:

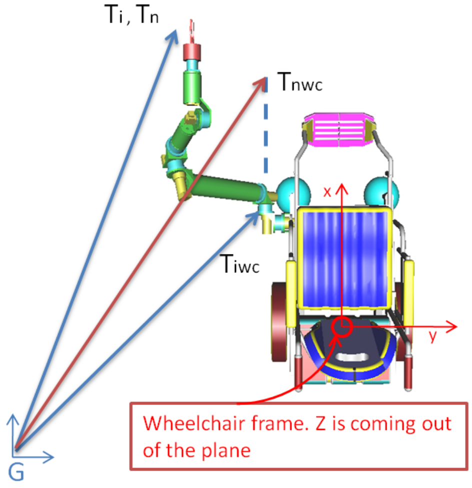

Fig. 1. Motion Scheme

$$\dot{q}_c = J_c \centerdot J_W \centerdot V_c \qquad (1)$$

where $\dot{q}_c = [\dot{x}\,\dot{y}\,\dot{z}\,\dot{\alpha}\,\dot{\beta}\,\dot{\phi}]^T$, $V_c = \begin{bmatrix} \dot{\theta}_l \\ \dot{\theta}_r \end{bmatrix}$,

$$\mathrm{J_c} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^{\mathrm{T}}$$

and

$J_W =$

$$\frac{l_5}{2}\begin{bmatrix} c\phi_c + \frac{2}{l_1}(l_2 s\phi_c + l_3 c\phi_c) & c\phi_c - \frac{2}{l_1}(l_2 s\phi_c + l_3 c\phi_c) \\ s\phi_c - \frac{2}{l_1}(l_2 c\phi_c - l_3 s\phi_c) & s\phi_c + \frac{2}{l_1}(l_2 c\phi_c - l_3 s\phi_c) \\ -\frac{2}{l_1} & \frac{2}{l_1} \end{bmatrix}$$

The wheelchair will move forward when both wheels have the same speed and direction while rotational motion will be created when both wheels rotate at the same velocity but in opposite directions. Since the wheelchair's position and orientation are our control variables rather than the left and right wheels' velocities, V_c can be defined as:

$V_c = \begin{bmatrix} \dot{X} \\ \dot{\phi} \end{bmatrix}$, where $\dot{X}$ and $\dot{\phi}$ are the forward and rotational velocity respectively, and are defined as:

$$\dot{\phi} = \frac{2 l_5 \dot{\theta}_r}{l_1}$$

, and

$$\dot{X} = l_5 \dot{\theta}_r$$

Seven DoFs are provided by the robotic arm mounted on the wheelchair. From the DH parameters of the robotic arm specified in earlier publications [9], [14], the 6x7 Jacobian that relates the joint rates to the Cartesian speeds of the end effector based on the base frame is generated according to Craig's notation [15]:

$$\dot{r} = J_A \centerdot V_A \tag{2}$$

where $\dot{r} = [\dot{x}\, \dot{y}\, \dot{z}\, \dot{\alpha}\, \dot{\beta}\, \dot{\gamma}]^T$ is the task vector, and

$V_A = [\dot{\theta}_1\ \dot{\theta}_2\ \dot{\theta}_3\ \dot{\theta}_4\ \dot{\theta}_5\ \dot{\theta}_6\ \dot{\theta}_7]^T$ is the joint velocities vector, and

J_A is the Jacobian of the robotic arm.

Combining the wheelchair and arm kinematics yields the total system kinematics. In the case of combined control, let the task vector be:

$$r = f(q_c, q_A), \tag{3}$$

where q_c and q_A are the control variables of the wheelchair and arm respectively. Differentiating (3) with respect to time gives:

$$\dot{r} = \frac{\partial f}{\partial q_c} V_c + \frac{\partial f}{\partial q_A} V_A = J_c J_W V_c + J_A V_A = \tag{4}$$

$$= \begin{bmatrix} J_A & J_c J_W \end{bmatrix} \begin{bmatrix} V_A \\ V_c \end{bmatrix}$$

where J_c and J_w are the jacobians that map the end-effector velocities to the arm base velocities (without arm motion)

$\dot{r}$ can then be defined as $\dot{r} = J \centerdot V$. where $J = [J_A\, J_c J_W]$ and $V = \begin{bmatrix} V_A \\ V_c \end{bmatrix}$

3.3 Task Space Definition

When the first step starts for opening the door, we are able to utilize all 9 DoFs to perform the task. However, at the start of the second step to hold the door knob and move the WMRA forward, the task space reduces the redundancy of the system as 6 degrees of freedom are locked, given that the end effector position and orientation needs to be locked. The locked position task vector is defined as a function of the arm's pose:

$$r = f(q) = [x_i\, y_i\, z_i\, \alpha_i\, \beta_i\, \gamma_i]^T \tag{5}$$

Numerical solutions are implemented using the Jacobian to follow the user directional motion commands or to follow the desired trajectory. Manipulability measure [8] is used as a factor to measure how far is the current configuration from singularity. This measure is defined as:

$$w = \sqrt{det(J_A \times J_A^T)} \tag{6}$$

We use S-R Inverse of the Jacobian [8] to give a better approximation around singularities, and use the optimization for this sub-tasks. S-R Inverse of the Jacobian is used to carry out the inverse kinematics:

$$\underline{J^+} = \underline{J^T} \times \left(\underline{J} \times \underline{J^T} + k \times \underline{I_6}\right)^{-1} \tag{7}$$

where I_6 is a 6x6 identity matrix, and k is a scale factor. It has been known that this method reduces the joint velocities near singularities, but compromises the accuracy of the solution by increasing the joint velocities error. Choosing the scale factor k is critical to minimize the error. Since the point in using this factor is to give approximate solution near and at singularities, an adaptive scale factor is updated at every time step to put the proper factor as needed

$$k \quad = \quad \begin{cases} k_o \times \left(1 - \frac{w}{w_o}\right)^2 for\, w < w_o \\ 0\, for\, w \geq w_o \end{cases} \tag{8}$$

where w_0 is the manipulability measure at the start of the boundary chosen when singularity is approached, and k_0 is the scale factor at singularity. It was found that the optimum values are ($w_0 = 2.0$) and ($k_0 = 0.35x10-3$) for our system.

3.4 Motion Planning

The complete task of opening the door starts with the subtask of "go to and open the door" performed in [7]. The last step of that subtask is illustrated in figure 3a. For the task of relevance in this paper, the task space is defined by the constraint imposed to keep the arm locked in place, and it can be better described by the motion scheme on figure 1. Figure 2 presents a flowchart diagram of the complete task, sub-tasks and the strategies implemented.

$${}^G T_i = {}^G T_n \tag{9}$$

T_i andT_n are the initial and n^{th} transformation matrix of the end effector. The n^{th} transformation matrix of the end effector needs to be compensated continuously by the rate of change of transformation matrix of the base (figure 1).

$${}^W T_n = {}^G T_i \cdot {}^G T_{iwc} \cdot {}^W T_{nwc}^{-1} \tag{10}$$

T_{iwc} is the initial transformation matrix of the arm base, and T_{nwc} is the transformation matrix of the arm base for a n-step during the motion.

This constraint is imposed by the task defined in the previous change, which is to lock the 6 Cartesian coordinates of the end effector. This allows the wheelchair to move forward, while the joint angles are calculated so that the end effector remains within the task space in the same initial transformation T_i. This sub-step is the initial wheelchair advancement and it is illustrated in figure 3b.

Ideally the wheelchair should go all the way through until it gets to a position in which it could keep the door from closing if released. This is not possible without losing the manipulability measure defined in (6). When the manipulability measure gets close to the boundary value $w_o$the system will increase the error propagation in order to stay away from singularities. For this reason, special care is taken to the manipulability measure throughout this entire application and preventive measures are taken into account to keep the achieve the main task. Even though the manipulability measure depends solely on the arm's configuration, Changing the orientation of the mobile base while keeping the end effector locked in position and orientation creates a new joint

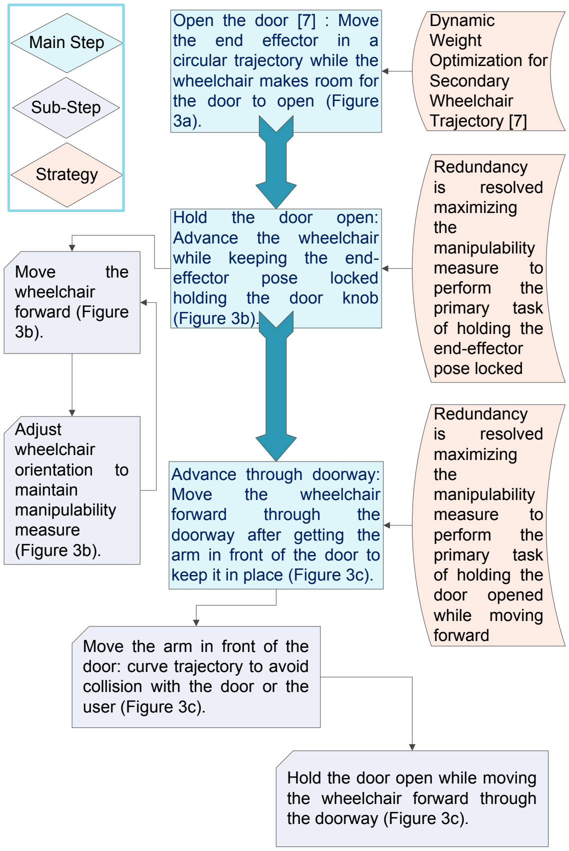

Fig. 2. Complete Task Flowchart

configuration thus modiying the manipulability measure of the 7 Dof arm.

Weighted Least Norm solution proposed by [16] is integrated to the control algorithm to optimize for secondary tasks. In order to put a motion preference of one joint rather than the other (such as the wheelchair wheels and the arm joints), a weighted norm of the joint velocity vector can be defined as:

$$|V|_W = \sqrt{V^T \cdot W \cdot V} \tag{11}$$

where W is a 9x9 symmetric and positive definite weighting matrix, and for simplicity, it can be a diagonal matrix that represent the motion preference of each joint of the system. In previous work a model to control a second trajectory for the wheelchair and the end effector was implemented in simulation by creating a dynamic weight matrix W to penalize or prioritize the motion of the wheelcahir compared to the arm [7]. This is used in this application as a way to keep the arm away from singularities. Having this weight matrix allows to keep the wheelchair moving forward or rotating as needed in order to keep the manipulability measure away from w_o. Having the task vector defined, and the weight matrix in the optimization algorithm, motion can be planed to perform the task while keeping the arm away from singularities.

When the manipulability measure decreases close to w_o, wheelchair orientation and position are changed to increase the manipulability measure. Figure 3b shows how the wheelchair rotates to compensate for the manipulability measure keeping $T_i = T_n$.

At this point the door will be released to rest on the front left portion of the wheelchair and the next step will be to get the arm in front of the door. Before this step, a quick exploration of the optimum pose for the wheelchair is made while keeping the manipulability measure as high as possible. This solutions are also constrained to the non-holonomic nature of the wheelchair. More details on the treatment of the non-holonomic nature of our system can be found in previous publications [7], [9]. If a better solution for the arm's manipulability measure is found with a different wheelchair pose, the wheelchair position will be refined further before releasing the door. Figure 4 shows a plot of the manipulability measure across the performed task. The manipulability measure is the trigger for the wheelchair pose adjustment in order to achieve the primary task. When the manipulability measure starts to get closer to $w_o = 2.0$ found in [9] for our system, the wheelchair pose adjustment takes place, increasing the manipulability measure to continue the task without approaching singularity. From figure 4 at around 20 seconds, the manipulability measure fluctuates when the wheelchair posed is changed to improve it.

Once the door is released, the next step is to get the arm in front of the door. This trajectory is constrained by the door as an obstacle, an invisible bounding box in which the user will be located, and the joint limits of the arm. Thus this trajectory can be made freely in the workspace as long as it keeps away from these constraints. Generally it is a curvilinear trajectory in 3D space in which there is no constrain in regards of the end effector pose or orientation. Figure 3c illustrates this step. The door used in simulation follows the standards of the International Building Code [11] and has a width of 33 inches (the minimum width is 32 inches). The WMRA system is mounted on a Quickie S-626 power wheelchair 24 inches wide [12] and the arm adds 4 inches in its folding position. This gives us 6 inches of room to get the system through the doorway.

Once the arm is in front of the door, the next step is to push the door back and then proceed going forward through the door way. Figure 3c shows in the upper illustrations the process of pushing the door, and in the lower part the wheelchair moving forward. This is the final step to complete this task.

IV. CONCLUSIONS AND FUTURE WORK

A complete task of opening a spring loaded door was performed in simulation using 9 DoF redundant mobile manipulator. Especial attention was paid to the end effector stationary pose while the non-holonomic wheeled base moved towards the doorway. Redundancy was resolved to maximize the manipulability measure during the task performance to minimize the Cartesian error in the end-effector pose. The wheelchair motion was used to compensate for the decrease in manipulability measure in the main sub-tasks. The dexterity of our 9 DoF system is implemented to get

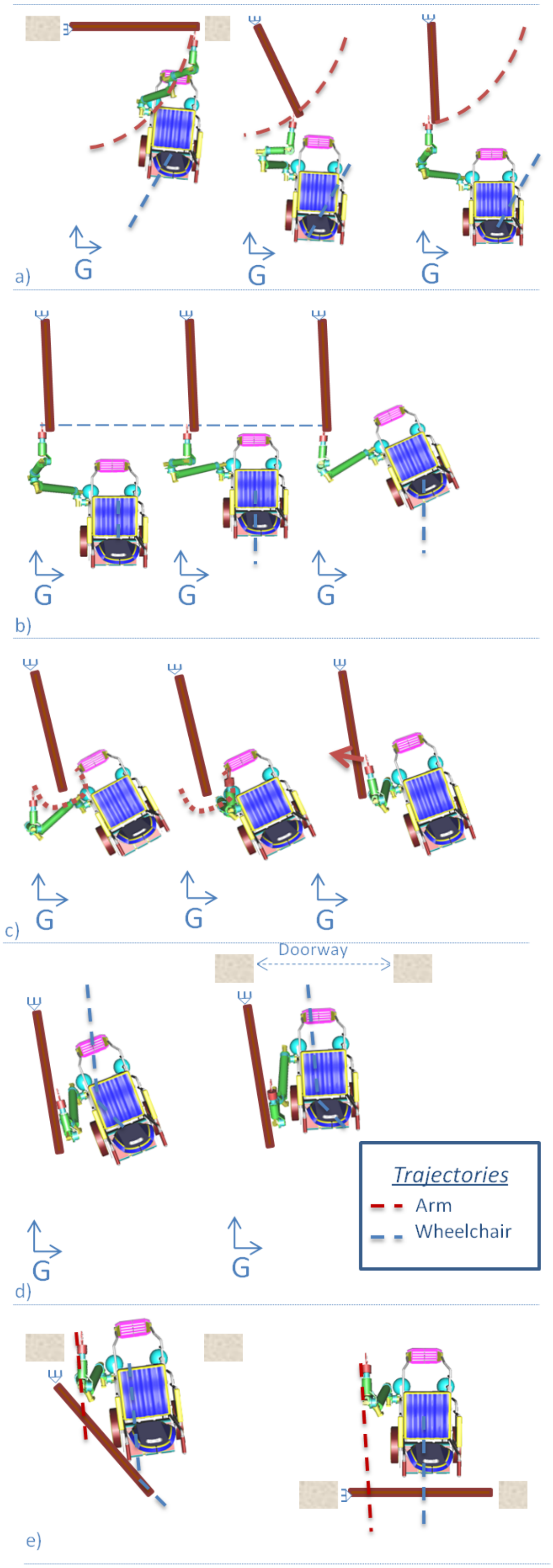

Fig. 3. Task Simulation. a) Opening the door while positioning the wheelchair to go through [7]. b) Holding the door open while advancing the wheelchair. Note the wheelchair orientation adjustment to maximize the manipulability measure. c) Moving the arm to door front and pushing the door open to advance through the doorway. d) Moving the wheelchair forward while maintaining the arm at a fixed position. e) Releasing the door and advancing the wheelchair through the doorway.

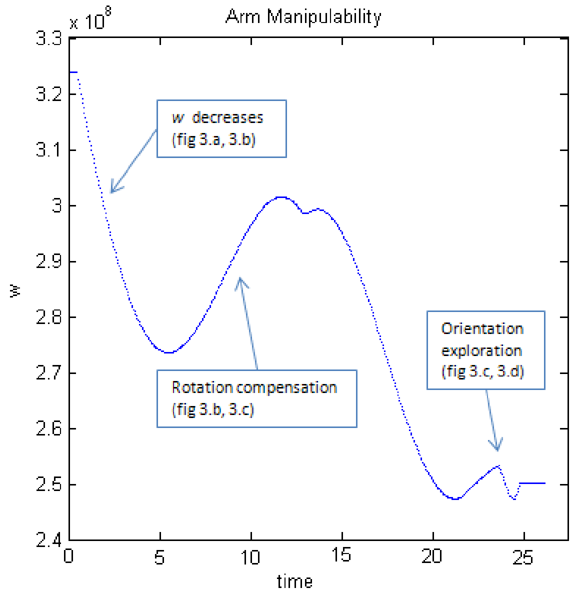

Fig. 4. Manipulability Measure when Holding the Door Open while Advancing the Wheelchair

the arm in front of the door to push it back in order to proceed forward through the doorway. This work expanded on the concept of dual trajectory control in our WMRA system for rehabilitation purposes with combined mobility and manipulation. The satisfactory performance of this task brings a variety of applications that can be explored in future work (search and rescue, aerospace, maintenance, automated production lines).

Future work will include a kinematic and dynamic evaluation of these concepts, and once this is done, we will proceed with implementation on the physical system. A sensory suite is being developed to address mobility and manipulation in unstructured environments and to provide autonomous inputs into the control system, reducing the user cognitive load even further.

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