Real-Time Teleop with Non-Prehensile Manipulation

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***Abstract*—In this work, we present a framework for teleoperation of manipulation tasks under low bandwidth, high latency conditions. This framework allows us to combine multiple manipulation and walking strategies to quickly adapt to changing mission parameters and conditions. In particular, this framework addresses the challenges of the hose attachment task of the DARPA Robotics Challenge, which encompasses walking with drag, grasping in constrained environments, and complex, close chain manipulation.**

I. Introduction

Humanoid robots are being developed with ever increasing capabilities. Current humanoids are capable of sensing and interacting at a very high level with increasingly complex environments. While the long term goal is to make these robots fully autonomous, it remains very challenging to implement this. Teleoperation, with shared autonomy with a human controller, is an emerging paradigm that has proved useful in allowing humans to control robots performing complex tasks. Our interest is in controlling a robot in an uncertain and dynamic environment through human interaction. This paper describes a teleoperated interface that combines high level sensing and low level control to allow a humanoid robot to perform a task with dynamic constraints. The task is part of the 2013 DARPA Robotics Challenge, which included tasks related to disaster remediation.

One of the key challenges of the 2013 DARPA Robotics Challenge preliminary trials is the changing guidelines and ambiguity of the trial descriptions. Participants in this challenge had a relatively short time horizon to develop a working framework for performing the tasks required by the trial, often while the underlying robot hardware underwent active development. In this paper, we discuss the approach taken by the DRC-Hubo team to the "Hose Attachment" task. In this task, the robot is required to attach a fire hose to a pipe mounted on the wall. This task combines several difficult issues. The hose is a flexible entity that is difficult to model and can change configurations. This makes automating the localization and grasp planning for the hose ending difficult. Additionally, the hose produces significant forces on the robot when being dragged along the floor or manipulated by the arm. These perturbations are very significant, because the final attachment of the hose requires extremely accurate positioning. In order to effectively address these complex and constantly evolving requirements, we have adapted a strategy for teleoperation of manipulation tasks that relies on a flexible, comprehensive interface of low level tools for well trained operators.

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II. Hardware

A. DRC-Hubo Base Platform

The DRC-Hubo (Fig. 1) is the latest version of the Hubo robot series developed by Rainbow Inc and KAIST in South Korea. It is designed to perform the practical tasks like driving a car, walking on rough terrain, climbing a ladder, breaking a wall, removing debris, turning a valve, opening a door, and grasping/dragging a hose in human-centered environments. Compared to previous versions, the arms and legs have been significantly lengthened to increase the robot's workspace. The maximum joint torque for each joint has been increased to approximately twice that of the previous version, hubo2 [1] [2] [3], to allow for handling tools and heavier objects. The DRC-Hubo's seven Degree-Of-Freedom (DOF) arms provide kinematic redundancy which brings more reliable motion in manipulation.

DRC-Hubo is 1.2m tall without a head and weighs 48kg without a battery. Each joint has a built in PD controller for position control. The pelvis of the robot contains a three-axis Inertial Measurement Unit (IMU). The IMU measures angular variation in roll, pitch and yaw of the body. A three-axis force/torque sensor (F/T sensor) is located in each of the ankles and wrists. These F/T sensors are used to measure the reaction forces and moments from environmental contacts. This sensor data is used for balance and compliance control in walking

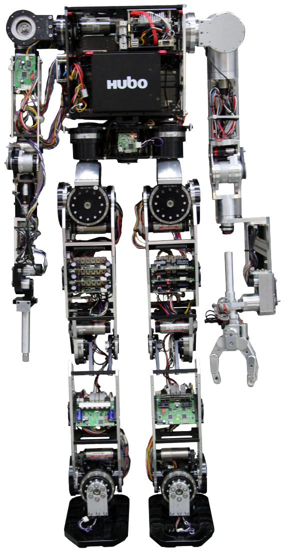

Fig. 1. The body of the DRC Hubo robot. It has 27 degrees of freedom: 6 in each leg, 7 in each arm, 1 in the left hand and 2 in the right hand. It is 1.2m tall and 48 kg. The main body contains an inertial measurement unit and each ankle and wrist has a force transducer.

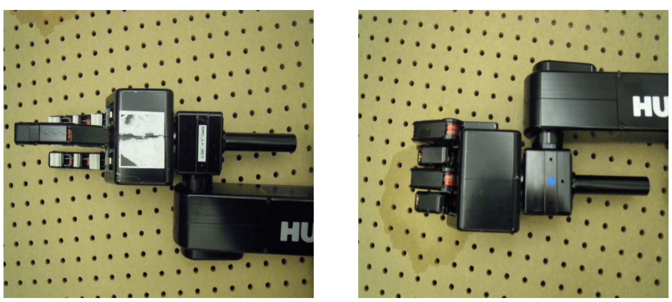

Fig. 2. The DRC-Hubo hands. *Left*: (a) The left hand with 3 fingers and 1 actuator. *Right*: (b) The right hand with 4 fingers and 2 actuators.

and manipulation. There is also a floor facing camera on the bottom of the torso for reviewing foot positions.

B. DRC-Hubo Hands

The design of DRC-Hubo arms is focused on 1) handling tools and 2) supporting the body. Both of the Hubo arms have the same base hand. The left hand in Fig. 2(a) has three tendon driven fingers with a single actuator. The right hand in Fig. 2(b) is similar, but has an additional 'trigger finger' with its own isolated actuator. This trigger finger is used for operating tools like an index finger. This is used in the DRC tasks for things like activating an electric power drill. All fingers are force controlled and generate a total grasping force up to 170N. The fingers are laid out so that they interlock while closing, which helps the hand stop from losing the grasp during operation. The base of each hand has a 'spike' pointing in the opposite direction of the palm. This spike was originally designed to support the robot in a quadruped walking stance using all four limbs. The quadraped walking stance allows the robot to travel underneath things like tables or tunnels under obstacles. In our tasks, we have found that the spike is also useful for non-prehensile manipulation in crowded spaces, because extending an individual finger is only possible using the trigger finger on the right hand, and the trigger finger is much less durable than the spike.

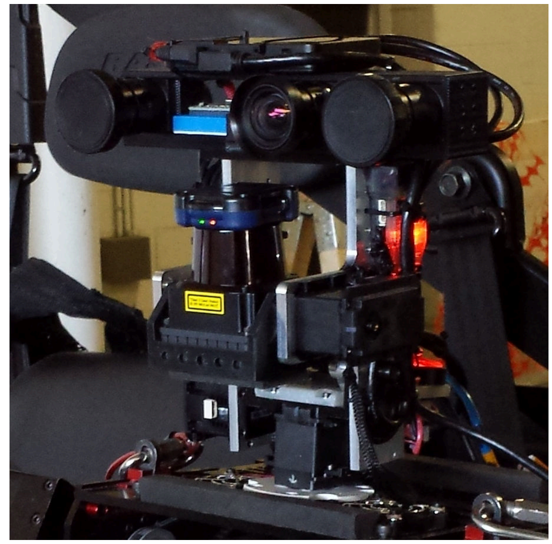

Fig. 3. The DRC-Hubo head that was mounted on the body for the DRC challenge. The head carries 3 stereo cameras as well as a Hokuyo laser scanner and an IMU. This head is 3-DOF, including a pan-tilt unit and a separate tilt unit for the Hokuyo scanner.

C. DRC-Hubo Head

The DRC-Hubo carried a sensor head, shown in Fig. 3, made up of a pan-tilt neck with an integrated IMU, and an additional motor for a tilting laser scanner. The head carries 3 stereo cameras along with a Hokuyo laser scanner. It also has a backward facing web camera, which is useful for walking backward and mounting stairs backward.

III. Robot Operation

In order to perform these tasks, we divide the responsibilities among three different individuals, each managing their own tool chain. The layout of the team and the strategy is shown in Fig. III. The task is broken down to piloting, sensor management, and situational awareness. The pilot is in charge of the task completion and control over the main actuators of the robot. The sensor manager controls the head of the robot to gather vision sensor information. The situational awareness manager organizes the informations gathered by the vision sensors so that it can be used by the pilot.

A. Sensor Head Manager

In this work, the stereo vision was not used. In general, conserving available bandwidth to allow the pilot responsive control over the robot was a paramount concern, and the main consumer of bandwidth was found to be vision sensor feedback. Walking and gross positioning of the robot were

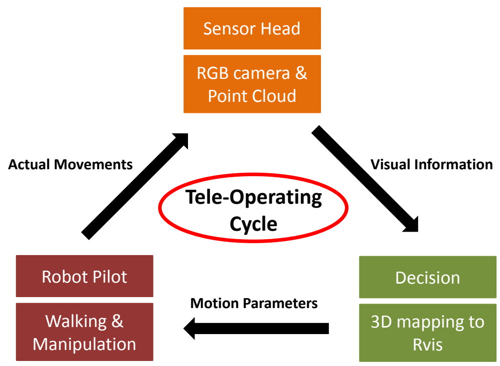

Fig. 4. Layout of system operation. One person is responsible for generating sensor data and visual measurement, a second person organizes the information to generate situational awareness, and a third person who is responsible for generating actual motion commands.

accomplished using only a low resolution black and white image from one of the stereo cameras. The sensor head manager was tasked with monitoring the quality of the communication channel to the robot and varying the sensor feedback's bandwidth usage accordingly to maintain the system's overall responsiveness. The sensor payload of the head is expensive and fragile, so while the robot was walking long distance or in uncertain terrain, the sensor head's actuators were placed into a compliant mode, so impact of environmental collisions or falls was minimized. The sensor head manager controlled the actuators on the head to point the sensors as directed by the pilot. They would also acquire a point cloud on demand, specifying the scanning window to minimize the bandwidth and acquisition time for the scan. The interface for the sensor head control is a set of custom dialogs implemented in RViz [6], where the pilot and sensor head manager visualize the current scene, as well as feedback provided by the situational awareness manager.

B. Situational Awareness Manager

In order to allow the pilot to make accurate decisions, the situational awareness manager aligns primitives to the point cloud provided by the sensor head. Multiple point clouds can be accumulated and manually aligned to one another. After roughly aligning entities, ICP can be used to refine this alignment. We use a 'virtual fixture' [5] approach, where each primitive has a set of target poses associated with it, each corresponding to a different manipulation type, which can then be manually refined along its major axes. The motion planner is invoked to test reachability to the target poses viable for the manipulation type directed by the pilot, and if a reasonable, reachable motion plan can be found, it is reviewed by the pilot for execution. For fine motions, the pilot can visualize the target pose and the cartestian distance to the current end effector pose for input to the online inverse kinematics controller. If there is no reachable plan, the situational awareness manager has tools to analyze the cause of the failure and suggest corrective actions to the pilot.

C. Piloting

The pilot has controls the robot base's motion through two Graphic User Interfaces (GUI) for walking and manipulation.

1) Walking: The walking algorithm consists of the real-time gait planner and controls. The gait planner [7] [8] takes the analytic solution of the gait based on an inverted pendulum model [9]. The gaits are generated using the parameters returned from situation awareness manager like distance to travel and angle to turn. Damping controller, vibration controller, early landing and moment compliance controllers, and Zero-Moment Point (ZMP) compensator are used for dynamic walking [7]. The dynamic walking algorithm is capable of walking at up to 0.3m/s, but is limited to relatively flat terrain with few obstacles. At more than ± 3 degrees of inclination, the dynamic walking becomes unstable. For these situations as well as walking over rough terrain and obstacles, we have implemented a slower, but more stable walking strategy based on similar strategies that will be presented in [11]. These two walking modes are switched corresponding to the ground roughness measured.

2) Manipulation: Gross motions are performed using a simple cosine velocity curve to connect sparse joint trajectory way points that can be computed in any planner. Finer motions are controlled online by the operator using whole-body Inverse Kinematics (IK) solver described in [10]. The whole-body IK solver used takes positions and orientations of four end-effectors (left and right hands and feet) and position of pelvis in world coordinate system in order to calculate the IK solution in numerical way. The joint redundancies are used to keep the Center of Mass (CoM) within the support polygon. The origin of global frame is located on the center of left foot.

This controller does not explicitly check for self collisions, and may allow the operator to enter self colliding or kinematically singular configurations, from which the operator cannot leave without sending the robot to a safe joint configuration. To ameliorate this issue, we use a motion planner that can find appropriate end effector positions for the tasks.

3) Planning: Gross motion trajectories are computed using the CBiRRT planner in OpenRAVE [4]. This planner allows a wide variety of constraints to be encoded. This is especially helpful for planning rotational motions and specifying end effector configurations that ignore rotations around the approach direction of the hand. Since there are only 6 DOFs between the torso and the hand spike, allowing rotations around the approach direction of the spike leads to a dramatically expanded workspace. Each subtask has different requirements for the size and shape of the workspace that will be needed for fine motor control. For example, acquiring the end of the hose requires the operator to move along the approach direction of the spike to insert the spike in to the end of the hose. An offline version of the inverse kinematics controller is used to filter the end effector goal poses to guarantee that these workspace constraints are met by the goal pose. After planning, potential trajectories and the expected followup motions used in the work space filter are visualized in the OpenRave virtual environment before execution so that the pilot can reject them after visual inspection. Commonly used trajectories that are expected to be executed in free space, and are thus not concerned with environmental collisions are cached.

IV. Hose Task

The main manipulation task accomplished with this pipeline was the hose attachment task of the DRC. This task was broken down into several subtasks with different requirements: acquisition, transportation, and connection. A diagram demonstrating the hose task is shown in Fig. 5 provided by the DRC competition. First, the robot has to acquire the hose end which is hanging from the reel. This requires the robot to walk several feet forward from the green line to the red hose reel mounted on the wall. From there the robot must turn and walk forward to past the yellow line. Then, the robot can reach forward and connect the hose.

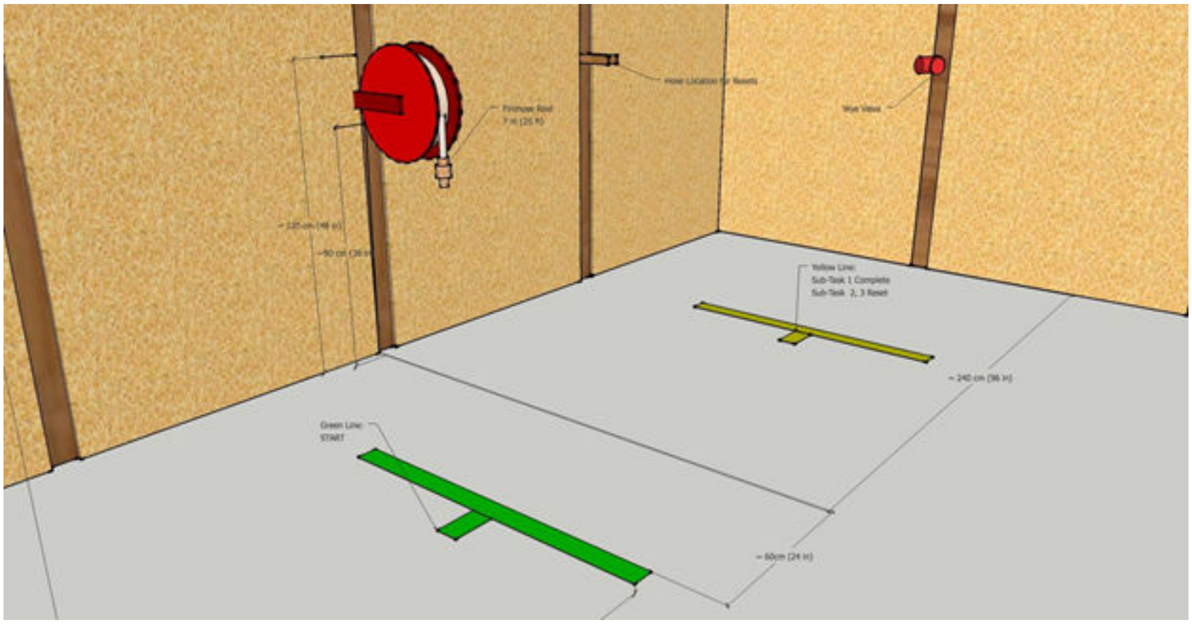

Fig. 5. A diagram of the hose task from the DRC task description. The robot begins behind the green line, walks forward to grasp the hose hanging on the reel, then walks across the yellow line to attach the hose to the wall mounted 'Y' shaped water outlet, called a wye connector.

A. Virtual Fixtures

A virtual fixture is analogous to using a ruler draw a straight line on a piece of paper. It is an element of an interface in a virtual reality environment that constrains the operators ability to manipulate objects in the scene to enforce constraints like alignment and reachability. In this work, we used virtual fixtures to allow the scene manager to quickly and accurately show the pilot reasonable goal poses for the manipulator. The scene manager accomplishes this by aligning simplified representations of the objects to manipulated with the point cloud provided by the sensor head manager. In this relatively simple scene, we are able to approximate all of the objects as cylinders or compositions of cylinders. Each subtask defines a particular fixture, represented as a transform with respect to one of the cylinders and a set of cartesian direction vectors representing the direction along which the pilot is expected to move to the manipulator to interact with the object after gross motion planning is finished. In addition to allowing the pilot to quantify the movement needed to achieve the desired manipulation, the fixture also indicates whether the goal point is reachable by querying the manipulation planner, and changing colors if the goal is not feasible from the robot's current location. The fixtures available for these tasks are shown in Fig. 6. These fixtures include a hooking motion, a power grasping motion and transportation motion, and a connecting motion meant to turn the coupling of the hose with the hand spike.

B. Hose Acquisition

The hose end hangs close to the reel, which is secured only by some painters tape. Since the hand has only a single motor without encoders, preshaping the hand to grasp the hose end without hitting the reel and knocking the hose end loose is difficult. Instead, we use a non-prehensilze grasping strategy in which we insert the 'walking spike' of the left hand into the hose end. This strategy is significantly more robust, since we simply align the the spike to the end of the hose more or less agnostically with respect to normal direction, then simply approach straight along the approach direction until the hose is seen to move in the low resolution image.

C. Transportation

Second, the robot has to walk several feet while pulling the hose. After walking forward several feet, we execute a preplanned trajectory moving the shoulder up to drag the hose forward to reduce the drag. The operator uses a grayscale image to keep the heading of the robot set towards the 'Y' shaped water outlet, called a wye connector.

D. Connection

When the robot has finished the first point of the task, the hose end is switched to a power grasp in the right hand by executing a set of preplanned movements. First the robot brings the arm forward to get slack in to the hose to reduce

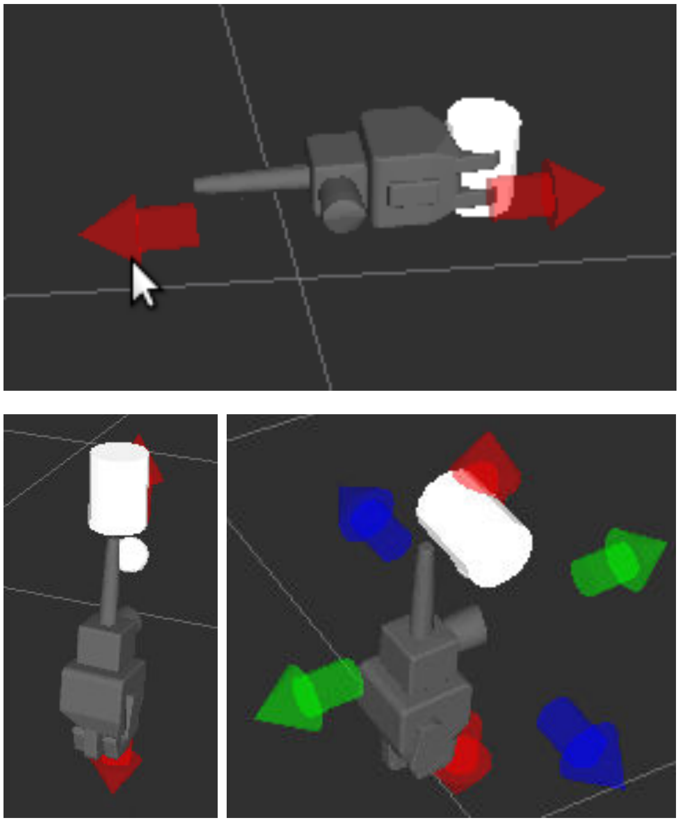

Fig. 6. An illustration of the 3 manipulation fixtures associated with a cylinder object for this task. On top is a power grasp of the hose end and positioning the hose end the environment. Bottom left is a hooking motion for not prehensile grasping by inserting the peg in the end of the hose. On the bottom right is a starting posture for pushing the rotating threads at the end of the hose.

the drag on the arm. Then the hose is hose is swapped from the left hand spike to a grasp in the right hand. From there, a trajectory is planned to align hose end to the connector. Finally, a movement to align the left spike to the hose end, which can then be manually controlled using real-time inverse kinematics to rotate the hose end and complete the connection. Because this manipulation requires extremely accurate, this fixture allows refinement of the goal pose along all three axes of the cylinder.

V. Conclusion

In experimental trials, we have found that the system described above sufficient to robustly achieve the first two points of the task within 20 minutes even on a connection with intermittent low bandwidth and high latency, which was a reasonable goal post for this stage of the DRC challenge. We found that it was not worth investing resources in complex, robust autonomous behaviors in the face of changing requirements, and instead focused on improving the robustness of lower level teleoperation. In practice, this approach leaves us with ten minutes to attempt the third point of the task, which is considerably more demanding in terms of precision, and is therefore hit or miss in teleoperation. In fact, a human aligning the hose end to the wye connector will often have difficulty achieving the precision required to engage the threads of the connector. In order to improve performance on this stage of the task, we intend to integrate more teleoperator feedback for the force torque sensors as well as creating self-aligning movement primitives that move until a desired force-torque measurement is read.

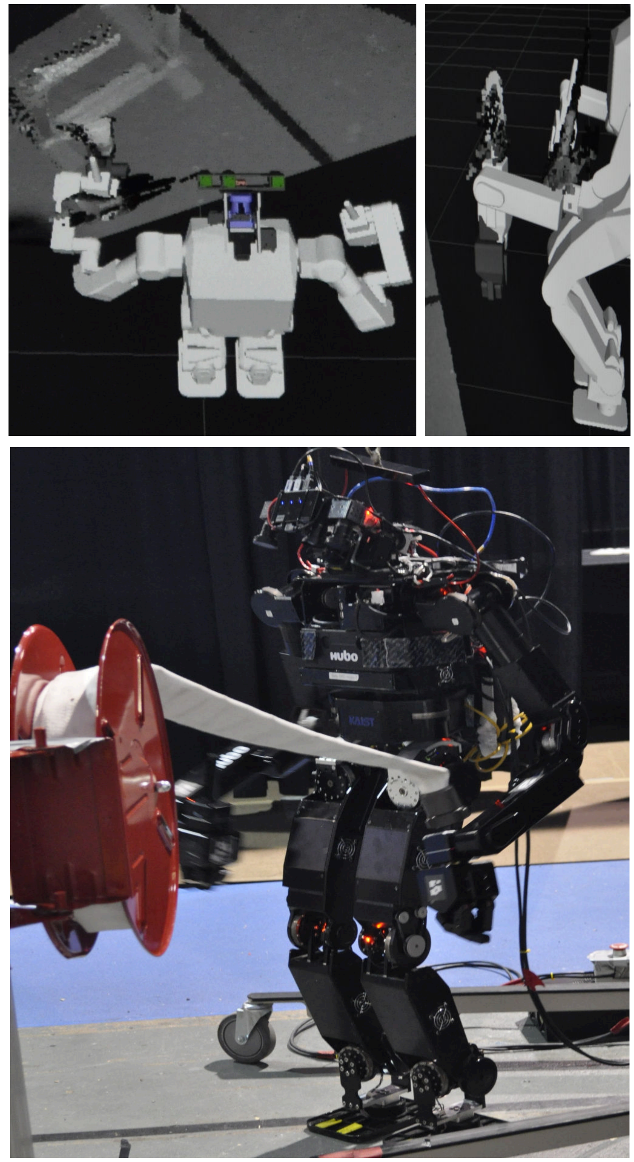

Fig. 7. An illustration of the DRC-Hubo performing the hose task. In the main image on bottom, you can see the DRC-Hubo having acquired the hose on the hand spike and dragging it back to turn towards the wye in a practice run. On the top left, we show the feedback from the vision system during hose acquisition. On the top right, we show the view of the robot's left hand spike aligned with the hose end during hose acquisition.

Acknowledgment

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