Towards Cooperative Control of Humanoid Robots for Handling High-Consequence Materials in Gloveboxes – 17291

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ABSTRACT

In this paper, we describe our ongoing work with NASA's Valkyrie humanoid robot and present preliminary results on cooperative control of Valkyrie's hands for performing dexterous manipulation tasks inside gloveboxes commonly found in many nuclear facilities. First, we discuss our human-supervised robot control framework which is based on optimization-based whole-body motion and manipulation controllers. A key aspect of this approach is perception based grasping. We develop a grasping control module for realizing the grasps corresponding to sample tasks such as power, ball, key, pinch, and open palm grasps and their variations. Next, we introduce the notion of motion template library in order to develop generalizable robot grasping and manipulation. Motion template library stores the constraint setting information for the constrained motion planning methods and a framework which can implement the motion template library on different types of robots for accomplishing similar tasks. Motion templates are defined only based on the task requirements. As a result, they can be easily ported to different robot platforms. Lastly, we discuss our multi-modal interfaces designs which include a visual display for improved situational awareness as well as a tactile glove for robot hand control and feedback. Our goal is for the person teleoperating the Valkyrie robot to have better sensing and control than what he or she would have if actually standing at the glovebox doing the work. This improved sensing is comprised of the ability to “see through” the robot’s arms and hands in the gloves and to have an improved sense of touch. The paper concludes with a discussion of our validation strategy. Our success metrics are derived from the completion of a relatively complex experiment to be performed in the glovebox. We evaluate various realistic experiments and use them for task validation and demonstration with Valkyrie. We use speed, time of completion, accuracy, repeatability and reliability rates as success metrics by designing replicable experiments.

INTRODUCTION

In December 2015, our team attended the Department of Energy, Office of Environmental Management (DOE-EM), Workshop on Robotic Handling of High Consequence Materials at the Savannah River Site (SRS) in South Carolina. During the 4-day workshop, participants had first-hand experiences observing various processes including nuclear material handling, liquid waste management, the deactivation and decommissioning (D&D) process, and glovebox operations. At the SRS, there are more than 3500 gloveboxes in use today. Each glovebox activity requires at least three workers: an operator, a radiological control inspector, and a supervisor. Even though safety is paramount in all DoE operations, accidents do sometimes occur [1]. In 2010, a technician received a puncture wound while working in a glovebox and the accident resulted in internal contamination with transuranic elements. How might we avoid such accidents that put skilled humans at risk? At the same DoE workshop, plans for decommissioning the 235-F Plutonium Fuel Form Facility were discussed. The planned activities include restoration of services to the Plutonium Fuel Form Facility (PuFF) gloveboxes, and decontamination of the gloveboxes. The airborne nature of Pu-238 existing in the gloveboxes makes the decontamination extremely dangerous for humans to perform. *How might we decontaminate gloveboxes in 235-F building without risking human lives?*

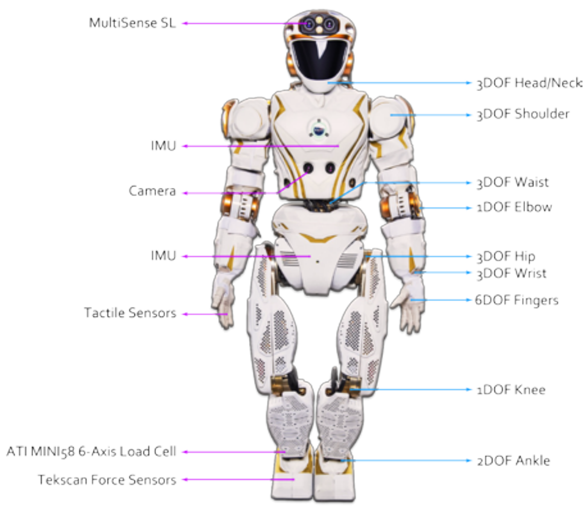

Figure 1: NASA Johnson Space Center's humanoid robot Valkyrie (R5)

Our overarching goal in this collaborative project is to evaluate the technological readiness of dexterous robot hands, such as those on NASA's humanoid robot Valkyrie, to replace human hands for safe and risk averse operations in existing gloveboxes in nuclear facilities. We are motivated by the fact that the dirty, dull and dangerous tasks ideal for robotics are extensively found in thousands of gloveboxes being used today. We will achieve our goal by (1) leveraging our team's expertise in human-supervised control applied to humanoid robots [3-6] and remote human-robot interaction [7-9], (2) developing a systematic model-based task validation methodology for common tasks performed in gloveboxes using our NASA-designed Valkyrie humanoid robot [2] (Government Furnished Equipment awarded to our research team), (3) implementing novel dexterous grasping and human-robot interaction techniques, and (4) developing supervised-autonomy techniques for constrained manipulation (both nonprehensile and dexterous) in confined spaces.

When teleoperating a remote robot, the lack of situation awareness afforded to the robot's operator can be a major problem. When humans move through an environment, our peripheral vision provides a wider view than cameras on most robot systems. Even when robot systems have wide angle cameras, the views require more interpretation on the part of the operator to understand the robot's surroundings, which can be overcome with training. However, when a person is wearing personal protective equipment (PPE), peripheral vision and other senses such as touch are also reduced. When a person in PPE is using a glovebox, his or her gloved hands are placed into another pair of thicker gloves attached to portals on the glovebox. The person is not able to see through the gloves, which obstruct the view of the working space. We often compensate for obstructions in one perceptual system by using another; in the case where we might not be able to see an object in front of us, we could pick it up to feel it. However, the multiple layers of gloves reduce the sense of touch. While a major goal of our research is to remove the human from the danger of the radiation environment, our primary goal is to make the robot teleoperation experience better than the in-person experience by providing superhuman senses. While a person cannot see through gloved hands, a sensor placed on the robot's hand, inside the two glove layers, could detect objects and create a point cloud that could be used to provide enhanced visual feedback to the teleoperator, by making the gloves transparent in the virtual reality headset and enhanced tactile feedback in gloves worn by the teleoperator.

NASA Valkyrie Humanoid Robot

Valkyrie, shown in Figure 1, is a 32 degree of freedom (DOF) humanoid robot originally designed by NASA Johnson Space Center. The robot consists of 5 major mechanical sub-assemblies: two arms, two legs, and a torso. The arms consist of a total of 7 DOF arranged in a 3 DOF shoulder, 1 DOF elbow, and 3 DOF wrist. The first 5 DOF of each arm are implemented through series-elastic actuators (SEA) enabling the implementation of torque and impedance control. The last 2 wrist DOF are implemented with a lead-screw on a linear guide assembly. The 7 DOF redundant arms allow for the optimization of trajectories and provides much needed flexibility in accomplishing tasks: for example, selecting between an elbow up and elbow down arm configuration. Each arm is equipped with a 6 DOF hand consisting of three 1 DOF fingers and a 3 DOF thumb. The thumb has independently controlled distal and proximal joint control in addition to roll control of the entire thumb assembly, allowing Valkyrie to touch each one of her other 3 fingers to her thumb. An array of pressure sensitive sensors encased in a rubber compound cover the fingers and palms of each hand giving the robot a tactile sense of objects that are grasped. There is no direct force sensing available on these actuators, so the low-level controller for the fingers is position based. Through a combination of using the barometers in the fingers and palm, force controlled grasps can be realized.

Valkyrie's head consists of a Carnegie Robotics Multisense SL sensor unit combining a rotating Hokuyo LIDAR and a stereo camera pair. An integrated FGPA in the Multisense SL processes the stereo camera data and provides registered point clouds from the camera data and LIDAR data. Integrated fully-dimmable LED lights can be used to illuminate the scene. In addition, the LIDAR rotation speed can be varied, trading off denser point clouds for longer scan times.

Valkyrie has two on-board computers: Link and Zelda. They are single board computers (SBC) with Intel i7-3615QE at 2.3 Ghz paired with 16GB of DDR3 1600 and a 240GB SSD. All of that is on a Congatec BS77 Type2 COM Express module and the EFK XV1 carrier board provides peripherals. Both computers run Ubuntu 14.04 Server edition, and Link, which runs the onboard low-level controllers, additionally has realtime kernel patches to ensure controller performance. In addition, it interfaces with the Synapse drivers implementing the custom LVDS Robonet protocol used to communicate with the motor drivers and sensor boards throughout the robot. In general, Link only runs the low-level controllers, and Zelda runs any ROS nodes that are needed on the robot, including handling the Multisense SL sensor data.

We will discuss our methodology and present preliminary results on humanoid robot control, multimodal interface design and human-robot interaction design approach.

METHODOLOGY

Whole-body humanoid control

We will rely on online optimization to develop walking and manipulation controllers to generate a wide range of behaviors with grasp or footstep targets. In order to exemplify our approach, we will discuss our manipulation controller scheme for humanoids in further detail. For the manipulation tasks, the desired Cartesian motions for the robot are specified, such as, foot positions, hand positions and CoM locations. The motion planning optimizer formulates these motions as its costs and constraints, and computes a trajectory represented by the joint states at a set of waypoints. The general formulation of the optimizer is given by:

$$\min_{x} f(x) \tag{1}$$

$$\text{s.t.} \quad \begin{matrix} g_i(x) \geq 0, \quad i = 1, \dots, n_{ieq} \\ h_j(x) = 0, \quad j = 1, \dots, n_{eq} \end{matrix} \tag{2}$$

where f , g_i and h_j are scalar functions, $n_{ieq}$and $n_{eq}$are the number of the inequality constraints and equality constraints. This approach considers the robot kinematics only and represent the trajectory as a sequence of T waypoints. The variable x in (1) is of the form $x = q_{1:T}$, where $q_t \in \Re^K$ describes the joint configuration at the t-th time step for a system with K degrees of freedom. The cost function $f\,(x)$ can be written as:

$$f(q_{1:T}) = \sum_{t=1}^{T}((q_{t+1} - q_t)^T Q_1(q_{t+1} - q_t) + \ (q_t - q_{nom})^T Q_2(q_t - q_{nom}) + d_\Delta^T Q_3 d_\Delta)$$

where Q_1, Q_2, and $Q_3$are positive semidefinite weight matrices and q_{nom}represents a represents a nominal posture. These quadratic cost terms represent penalization of the weighted sum on the joint displacements between the waypoints, posture deviation from a nominal posture in joint space and posture error in Cartesian space. The first term can limit the movement of the robot and smooth the trajectory. The second term is used to satisfy desired joint variables when all the constraints have been met. Similarly, the third term is used to push links to specific positions and orientations. The posture error in Cartesian space can be obtained by calculating the distance d_Δ from a given configuration to a task space region [11]. The constraints for the optimization problem include:

- Joint limits constraint
- Joint posture constraint which can be used to lock the joint in some specific value at a given time step.
- Cartesian hand posture constraint
- Center of mass constraint in which the horizontal projection of the CoM is desired to be on the support convex polygon between the two feet.
- Collision avoidance constraint for generating a collision free trajectory is one of the most important features of a motion planner. But it is difficult to formulate collision constraints in a closed form for optimization-based motion planning. We use a hinge-loss function to set up the collision constraints. The

advantage of the method is that it can not only check for discrete collisions on each step but also integrate continuous-time collision avoidance constraints.

Therefore, to generate feasible motions for the Valkyrie robot, a variety of costs and constraints can be set, such as costs for joint displacement, knee and back angles, pelvis height and orientation, torso orientation, shoulder torque, and constraints for joint limits, self-collision, environment collision avoidance, feet position and orientation, and CoM location. These are general costs and constraints. Task specific costs and constraints will also be used.

Constrained motion planning and control for risk-averse task completion

It is essential to develop dexterous manipulation capabilities for humanoids to advance their technological readiness for deployment in realistic situations. As a result, we are implementing methods to perform human-supervised dual hand tasks inside gloveboxes. It is noted here that our Valkyrie's hands are constrained when they manipulate a common object such as opening the lid of a bottle. Furthermore, glovebox ports also pose additional constraints. As a result, it is necessary to develop a unified motion planning and control framework in order to reliably complete human-in-the-loop tasks.

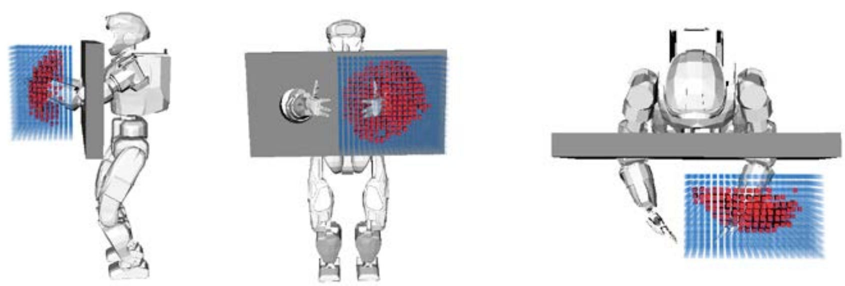

Figure 2: Workspace visualization for Valkyrie when both arms are inside the glove ports.

Our recent work in this area include the introduction of a template-based human-supervised robot task programming. To extend the application range to other manipulation tasks and other robots, we integrated our technique with the idea of the "affordance templates", which allows an operator to assign affordances manually to bootstrap application and task programming. However, instead of defining object affordance template with multiple candidate end-effector targets or a sequence of end-effector poses, we combine it with the motion template which stores the configuration information of the task level costs and constraints for the motion planning problem. Moreover, instead of using inverse kinematics (IK) to solve the joint configurations for each of the candidate end-effector poses, our method directly generates the optimal grasping pose and the whole motion trajectory at the same time. To generate a motion to interact with an object, task level constraints, whose parameters highly depend on the object configuration, need to be set in the trajectory optimization problem. The object configuration can be easily obtained using an object affordance template tool which can describe objects by allowing operators to instantiate an object template and to interact with it, moving it to desired location and adjusting its dimensions. Once the object configuration is satisfied from the adjusted affordance template, the task level constraint templates for some basic motions can be defined such as grasping and turning. For grasping an object, if a delicate grasp plan is not necessary (the robot only needs to move its end-effector to some place and then close the hand), an abstraction shape can be used to describe the grasping place. The object affordance template provides many primitive shapes such as cubes, spheres and cylinders. An arbitrary shape object, such as a toy, can be treated as a sphere, and the hand can approach it from any direction as long as the end-effector frame can reach the origin of the sphere.

Visual display for improved situation awareness

For the visual display, we evaluate the effectiveness of using a virtual reality headset, such as the Oculus Rift. Because the virtual reality headset is immersive, it can make some users feel motion sick. In order to allow our system to be used by a wider span of the population, we are developing both for virtual reality headsets and for a video monitor. This concurrent develop also allows us to test the effectiveness of these two approaches side by side, to determine the best methods for displaying information about the remote environment to the operator.

We conducted a study of human-robot interaction at the DARPA Robotics Challenge Finals that showed that providing multiple fused views of sensor data is more effective for remote operation of a humanoid robot than providing a single view of the data. All but one of the 20 teams in the study (of 23 in the DRC Finals) used some type of sensor fusion to combine multiple types of data into a single reference frame. This was done in two ways: using the point cloud as the reference frame for a variable perspective that could be dynamically adjusted (Type 1) or using the camera view as the reference frame for a fixed perspective (Type 2). Of the 19 (of 20) teams that exhibited sensor fusion, 6 (32%) only used Type 1 and 13 (68%) used both Type 1 and Type 2. Teams who used both types of sensor fusion views made significantly fewer errors, completed more subtasks, and fell less when comparing all mobility subtasks than Type 1 teams. When comparing all manipulation subtasks, teams who used both types performed significantly faster than teams with just the variable perspective.

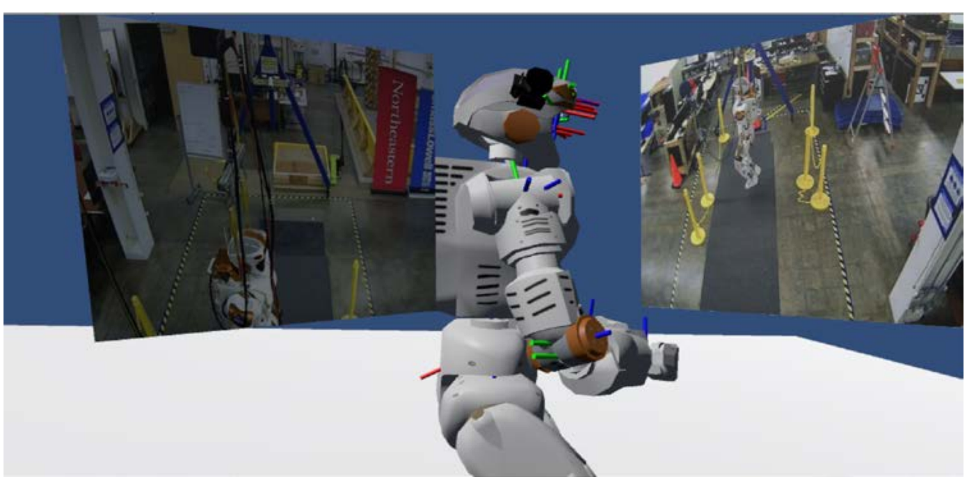

Figure 3: VIrtual reality display of Valkyrie's robot model with two displays streaming camera views from the task space.

The data displayed is gathered from the MultiSense stereo camera system in Valkyrie's head, and will include point clouds and video images. We are also integrating the point cloud information to be gathered from Valkyrie's touch sensors and a capacitive proximity sensor array that we are developing. The combination of the MultiSense data with the capacitive proximity point cloud from the robot's hands will allow us to develop an interface that can "see through" the robot's hands to the object being manipulated. Without such a capability, much of the teleoperation view will be of the hands and arms of the robot wearing the gloves in the glovebox, just as already happens for humans using gloveboxes.

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