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Achieving Versatile Manipulation Tasks with Unknown Objects by Supervised Humanoid Robots based on Object Templates

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***Abstract*— The investigations of this paper are motivated by the scenario of a supervised semi-autonomous humanoid robot entering a mainly unknown, potentially degraded human environment to perform highly diverse disaster recovery tasks. For this purpose, the robot must be enabled to use any object it can find in the environment as tool for achieving its current manipulation task. This requires the use of potential unknown objects as well as known objects for new purposes (e.g. using a drill as a hammer). A recently proposed object template manipulation approach is extended to provide a semi-autonomous humanoid robot assisted by a remote human supervisor with the versatility needed to utilize objects in the described manner applying affordances [1] from other previously known objects. For an Atlas humanoid robot it is demonstrated how using a small set of such object templates with well defined affordances can be used to solve manipulation tasks using new unknown objects.**

I. Introduction

Robotic manipulation is a well known problem in the research community. It considers different aspects such as the task objective, the object used and the manipulation requirements needed to fulfil the task objective. Fully autonomous robots operating in remote unstructured environments are challenged by constraints such as lighting conditions, reachability uncertainties, degraded communications, and unknown availability of objects. On the other hand, purely teleoperated robots require high bandwidth with low latency communication channels and demand a high mental workload from the operator, which limits their utility.

Human supervised semi-autonomous robots leverage strengths from both fully autonomous and purely teleoperated approaches. This combination reduces the cognitive workload of the operator by allowing communication through semantic commands. These semantic commands are then leveraged with powerful computing abilities of robots to perform autonomous tasks such as collision-free manipulation motion planning and Cartesian trajectory planning. The Object Template manipulation approach introduced in [2] demonstrated the ability to provide this kind of interaction. In this previous work, the versatility aspect of object manipulation was not considered as part of the concept for object templates. This paper adds to our previous contribution a formalization in the concept of transferring manipulation

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(a) Atlas attaching a fire hose (b) Fire hose template with affordances

Fig. 1: a) Developed by Boston Dynamics Inc. (BDI) the Atlas robot has 28 hydraulically actuated DOF, weighs approximately 150 Kg and stands 1.88 m tall is shown attaching a fire hose during the DRC Trials 2013. b) Shows the fire hose template, the potential grasp pose of the hand in translucent blue and in translucent green the available affordances of the fire hose, like the circular motion needed to tangle the threads while turning it (triangles around the template) and the Cartesian translation needed to push the fire hose against the pipe (salient arrow from the template).

skills from a known object to new unknown objects on the fly. In this context, the manipulation concept goes beyond the idea of how an object is grasped, and focuses on how an object should be moved around in the environment.

As motivated by the DARPA Robotics Challenge (DRC), a remote semi-autonomous robot should be capable of entering an unknown, partially degraded human environment to perform disaster recovery tasks. Utilizing a human supervisor in the loop to aid the robot with perception ability based on sensor data, the robot needs to be able to use available objects or tools found in the environment. During a robotic manipulation task, a human supervisor can remotely provide the robot with information of task objective and object locations in the environment. Still, accomplishing a remote manipulation task can be challenged by the lack of known objects in the environment. We present experiments that show how, using the approach in [2], a human supervisor can provide the robot with the versatility to perform manipulation tasks relying on the manipulation skills designed for some previously known objects.

A. Related Work

Improvisation is a powerful human ability that has not yet been deeply explored in robotic manipulation research. An interesting research approach by Stilman *et al.* presented the "MacGyver" paradigm as a research problem [3]. They propose that robots should be able to use arbitrary objects in the environment to solve unforeseen manipulation tasks. Performing these actions autonomously for unknown tasks in real world scenarios with degraded conditions is not feasible within the next years. Some autonomous approaches like [4], [5], and [6] have demonstrated autonomous capability for obtaining semantic information from objects. However, these approaches still require development to be able to perform autonomously in less controlled environments and unforeseen tasks. The idea of a robot applying manipulation skills to different objects has also been suggested by Leidner *et al.* [7]. In a semi-autonomous remote supervised approach, a human operator can effectively aid the robot to apply the necessary manipulation skills needed to achieve the task. Work focusing on supporting people with severe motor impairments with robots as assistive devices has been presented by Takayama *et al.* [8].

Şahin *et al.* [9] formalized the term of *affordance* [1] in the robotics field. This has been key to the development of robot control approaches [10], [11]. Object-Action Complexes (OACs) is a concept created by Kruger *et al.* [12] to formalize the relationships between objects and actions and defines affordances as state-transition functions that can be used for predictions. OACs give robots the possibility to understand how an object will behave after an action is performed and use continuous sensorimotor experience to build symbolic representations.

The approach in [13] presents the Affordance Template ROS package. Their approach provides a high level of adjustment and interactivity of the geometry information provided by the templates. They also introduce an Affordance Template Description Format which describes in an XML file the relationships between the used robot and the end effector waypoints needed to manipulate the corresponding template. Their user interface is based on the publicly available RViz interactive markers [14] which is analogously used in this approach. The approach previously presented in [2] is different given that grasp information is separately defined from the object information. The grasp library contains potential information of the robots end effector pose described in the template coordinate frame of reference, and the object template library contains, additional to the physical properties of the object (like mass, center of mass and inertia tensors among others), the affordances of the object. These affordances are defined as motion constraints like circular paths or Cartesian translations (either maintaining the end effector orientation or rotating along with the motion) commonly needed during manipulation of the object to achieve a particular manipulation task.

The approaches presented in [15], in [16] by MIT, in [17] by DRC-Hubo, and in [18] IHMC, also converge to an approach that analogously uses 3D geometric meshes with information about grasping capabilities. The differences are the way in which we define the possible actions to be executed over an object and how we interact with them. For example, to use the open and close affordances of a valve, the operator either manually rotates the template of the valve to create a motion plan or the user needs to previously define end effector waypoints like in [13]. In the approach presented here, the operator specifies a command such as "open" or "close" setting a number like "± 360 degrees" and on-line waypoints are then generated on the fly.

B. Overview

We participated in the DRC as Team ViGIR[1] with the highly advanced humanoid robot Atlas shown in Fig. 1. Team ViGIR is a cooperation between research groups in Germany and other research institutions in the USA. After our participation in the three main events, the Virtual Robotics Challenge (VRC) [19] in June 2013, the DRC Trials in December 2013 [20] and the very recent DRC Finals in June 2015, we are confident that the previously proposed object template manipulation approach can be used to perform manipulation tasks in unstructured environments using human supervision of a remote semi-autonomous robot. This paper adds to our previous contribution an approach to perform versatile robotic manipulation tasks in remote unstructured environments based on object templates. This approach increases the accomplishment potential of manipulation tasks by providing the ability to transfer manipulations skills from known objects to similar new unknown objects on the fly.

II. OBJECT TEMPLATES

This section briefly describes the concept of Object Templates. Detailed information is provided in [2]. Visually, an object template is a simplified 3D mesh of the object it represents, but implicitly contains physical and semantic information to aid the robot using it. Object Templates can contain physical object information such as mass, center of mass (CoM) and inertia tensor. Semantic information in an Object Template provides pre-computed potential pre-grasp and final-grasp poses, as well as information about their affordances as shown in Fig. 1b. We use an Operator Control Station (OCS) to manipulate object templates. The OCS helps in the visualisation of the sensor data acquired by the robot in an immersive 3D environment. Using the OCS a human operator can remotely identify the objects in the robot environment and overlap the 3D geometry mesh of the object template to the corresponding sensor data. The 3D pose of the Object Template can then be used by the robot for locomotion planing to walk towards the real object [21] and create motion plans to manipulate it. A demonstration of the use of Object Templates during the DRC Trials 2013 can be seen in [22].

The affordances in each template are defined as a pose $\in \mathbb{R}^3 \times \mathbb{SO}(3)$ used to create constrained motions paths between the initial and final end effector pose. We use linear interpolation to generate on-the-fly waypoints between the initial and final pose (details can be consulted in [20]). The end effector goal pose orientation can be different from the start pose thus the end effector will rotate along with the translation motion [23]. Motions that will constrain the end

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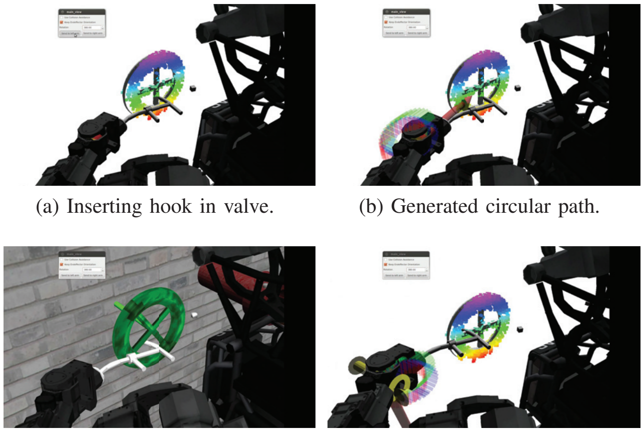


(a) Inserting hook in valve. (b) Generated circular path. (c) Rotating valve with hook. (d) Hook keeps orientation.

Fig. 2: Simulation experiment to turn a valve 360 degrees.

effector to keep its original orientation during the translation motion can also be generated. Circular paths around the axis of rotation of a template can be generated by concatenating multiple short linearly interpolated Cartesian paths (Fig. 2), which can also generate spiral motions, by combining both linear and circular motions simultaneously. This experiment can also be seen in this video[2].

Since the affordance based design is grasp agnostic, the operator can command the robot to generate a circular path to rotate around the axis of rotation of the template independently from the pose of the end effector. Waypoints are located over a plane normal to the rotation axis where this plane intersects the origin of the frame of reference of the hand. This way, the robot has the freedom to grasp the object in any way while still being able to calculate waypoints around the axis of rotation.

III. VERSATILE OBJECT MANIPULATION

This section describes the concept of versatility in the context of robotic manipulation using object affordances. Inspired by the work of [3] we propose a "MacGyver" paradigm for operator assisted humanoid robots. In this paradigm, versatile manipulation is the key ability to succeed in a particular task where expected known objects are not present. Versatile manipulation using the proposed approach allows for skills designed for previously known objects to be transferred to new unknown objects on the fly, utilizing the object template of a similar known object and provided that objects found in the environment have similar properties to previously known objects. In the context of this paper we talk about versatile manipulation in how tasks can be achieve by moving an object through the environment. We focus in defining affordances for some objects to achieve a task, and how a human operator either apply these affordances as designed, or utilizes them in a new way which was initially not planned.

[2]https://www.youtube.com/watch?v=wKFJO-Zkjck

As concluded by Liu et al. [24] in humans, grasps are distinguished by features related to the grasping action such as the intended motion, force, and stiffness. The ability of humans to transfer these properties between objects increases the rate of success in manipulation tasks. In a similar way, these properties are needed for robot control and the ability to transfer them between similar objects can help to achieve manipulation tasks. Doing this in a full autonomous way in unstructured and degraded environments is not feasible within the few next years. For this reason, the assistance of a human operator can help in identifying the tasks requirements and the objects that could be used to achieve them.

For example, consider the case where the robot enters a degraded environment and the human supervisor identifies the next task objective is breaking a glass panel to gain access to a fire hose or to allow smoke to dissipate. A commonly used object for this task would be a hammer. However, if a hammer is not be available in the environment, similar objects like debris, pipes or other tools that have similar properties to a hammer could be utilized with the same manipulation motions designed for using a hammer.

A. Object Classification

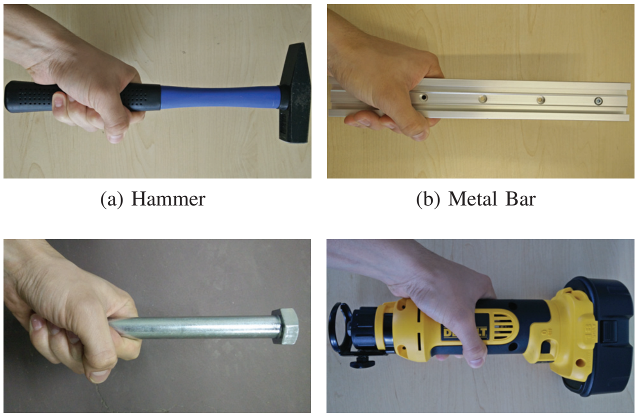
During a disaster scenario multiple objects from a wide variety of types can be found in the environment. In our approach, we will constraint the object space that our robot can use to objects that can be grasp and manipulated with a hand. To make clear the object space that we are considering we classify them in two groups:

1) Floating Objects: Refers to the objects mobile in the environment that can be grasped and lifted. For this reason similar physical properties between objects are needed to transfer affordances. Size, mass, center of mass, hardness among others need to be similar in such a way that the task might still be possible to achieve. In our hammering example, objects that would fit in the hand and that have the hardness and mass necessary to break a window could be used instead of the hammer as shown in Fig. 3.

2) Constrained Objects: Refers to the objects that have limited degrees of freedom in the environment. In this case, physical properties of the objects are not so relevant compared to the motion constraints that define the use of the object. For example, the drawer of a desk, a door handle and the door itself have motion constraints that can be defined as linear or circular motions with respect to an axis in a frame of reference as shown in Fig. 4.

B. Manipulation Classification

In this section we describe the classification of manipulation tasks that we are considering in our approach. To be able to transfer manipulation skills between two similar objects it is important to define in detail which properties of each manipulation motion are needed to accomplish a task. We constraint our approach to a representative set of manipulation tasks based on the classification of human



(a) Hammer (b) Metal Bar

(c) Bolt (d) Vertical Drill

Fig. 3: Floating objects. Mass, center of mass, hardness and size properties are similar enough to use them to create a force impact into another object.

(a) Door and Handle (b) Sliding Door (c) Drawer

Fig. 4: Constrained objects. Degrees of freedom are well defined, the door and handle have one axis of rotation, the drawer and the sliding door have one axis of translation.

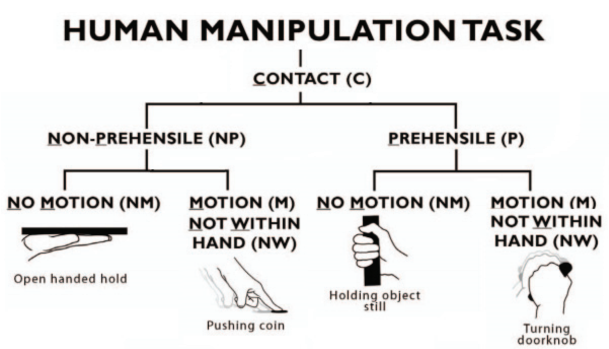


Fig. 5: Manipulation classification to be used in our approach. Image based on [25].

manipulation behaviour made by Bullock et al. in [25] as seen in Fig. 5.

Based on the manipulation properties described by [26] and [27] we selected the six classes which are identified to be most commonly used in manipulation tasks. The nomenclature used to identify each class represents the constraints for the six degrees of freedom (6DOF). This representation uses four letters, each of them represents a type of motion in a dimension. The letters used are "u" for unconstrained motion, "t" for a motion that is only translational, "r" for a motion that is only rotational, and "x" to represent a fixed constraint. The selected classes can be seen in Table I.

Class	Description	Example
uuu	Free Motion	Moving a floating object
uur	Point on a plane	Drawing on a white board
ttr	Surface against surface	Cutting with a vertical drill
uxx	Cylinder in slot	Attaching a hose to a pipe
rxx	One rotational DoF	Turning a doorknob
txx	One translational DoF	Pulling a drawer

TABLE I: Manipulation classes to be used in our approach. Table based on [27].

C. Manipulation Transferring Types

We have defined three different types of examples to differentiate the ways in which a manipulation task can be achieved using our approach. Each one of these example types represent a way of transferring manipulation skills; we describe them as follow:

1) Type 1: Transferring manipulation skills between objects in which physical properties can differ, but that they can still be considered to be the same object. For example, turning valves of different radius or with different number of cross bars, pulling drawers of different shapes and lengths. This is a simple way of transferring skills between objects, and the cases where objects are exactly the same is considered as a special case of this type of manipulation transferring.

2) Type 2: Transferring manipulation skills between different objects, but with same manipulation classes. This means that the affordances of the objects can be utilized in the same way. For example, a common doorknob manipulation class is "rxx" which allows rotation in only one axis, this means we can use the turn affordance of the valve template which belongs to the same manipulation class. Pushing a box under a table requires a manipulation class "txx" which can be achieved by using the push affordance from a drawer. This type of manipulation transferring shows how a robot is capable of using an object based on manipulation skills designed for another object in a way that will allow the robot to achieve the task goal.

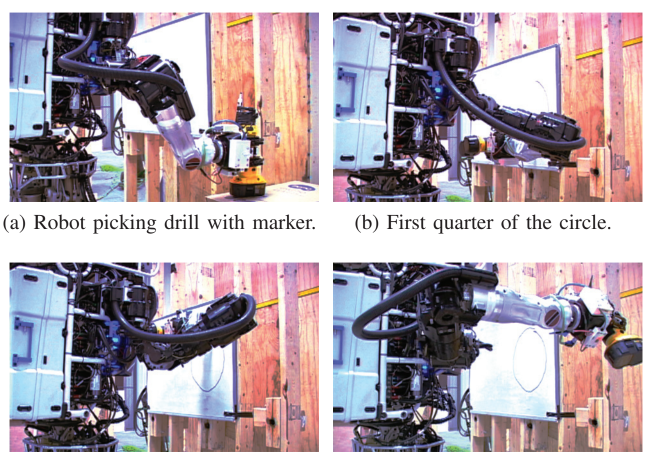
3) Type 3: Transferring manipulation skills through the use of intermediate objects. This type of manipulation skill transferring can be seen as the "MacGyver" paradigm described in this approach. This refers to how the robot is capable of manipulating an object for a different purpose than the one it was designed for and potentially utilizing manipulation skills from another object. The improvisation ability is still provided by the human supervisor, but it is now possible for the human supervisor to transfer manipulation skills from previously known object allowing the robot to use new unknown objects. This increases the potential of the human-robot team to continue the manipulation task.

IV. EXPERIMENTS

In this section we show experiments that demonstrate how being able to transfer affordances from one object to another or manipulating objects in a way they have not been used before can increase the potential to achieve a manipulation task. Experiments of type 1 will be used to demonstrate that the basic manipulation skills can be performed by the humanoid robot, also shown in [2]. Experiments of manipulation skill transferring types 2 and 3 directly represent the proposed approach in this paper.

A. Drawing a Circle: Type 1

In this experiment we show a test designed to evaluate the necessary manipulation skills that will be required to cut a circle from a dry wall using a vertical drill. To test these motions, we installed a black marker instead of the drill bit, and used a white board to show the path that the drill is following. The manipulation class required to cut a circle in a drywall using a vertical drill is “ttr” which means that the drill should always be perpendicular to the drywall plane and that can be translated in upwards and downwards directions. The affordances of the vertical drill can then be used to draw a circle in a whiteboard since both manipulation tasks belong to the same class as shown in Fig. 6.



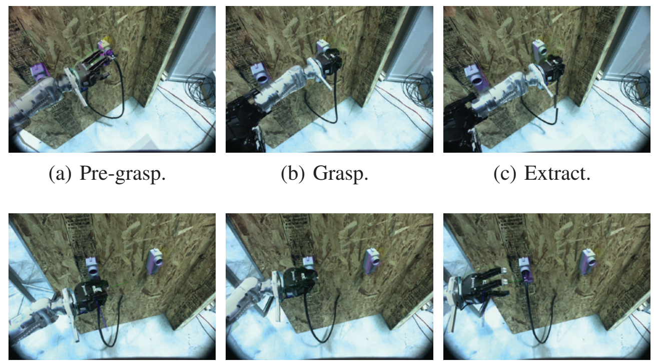
(a) Robot picking drill with marker. (b) First quarter of the circle.

(c) Three quarters of the circle. (d) Completed drawing circle.

Fig. 6: The robot generating a clock-wise circular path to draw a circle in a whiteboard, but using the “cut circle” affordance of a vertical drill. Video available as multimedia attachment.

B. Plugging a Cable: Type 1

In this experiment we show a laboratory experiment from one of the surprise tasks that was used during the DRC. The plug task consisted of unplugging a cable from a magnetic socket and plug it into another magnetic socket located within a reachable distance of the robot as shown in Fig. 7. The manipulation class required to plug a cable in a socket is “uxx” which means that the cable should always be aligned to the socket axis of insertion. This manipulation class is the same as the one required to attach a hose to a pipe [22] thus it was straight forward for the operator to utilize the affordances of the fire hose template.



(a) Pre-grasp. (b) Grasp. (c) Extract.

(d) Pre-insert. (e) Insert. (f) Release.

Fig. 7: Robot first person view of cord-plug surprise task. The task requires the cable to be unplugged from the right socket and be plugged to the left socket.

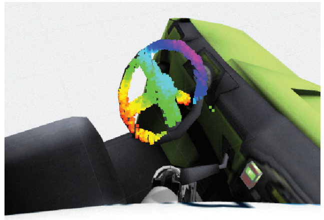
C. Steering Wheel: Type 2

In this experiment a human-robot team has been prepared for tasks involving valve manipulation (opening and closing). But in this case, the robot runs into a situation where using a car is needed and the robot has no previous knowledge of how to manipulate a steering wheel. The steering wheel is a constrained object of class “rxx”, it can only rotate around one axis. Assuming the robot can take a sit in the vehicle, the operator can then utilize the valve template to operate the steering wheel. Since the affordances of the valve template can produce the same necessary movements to turn a steering wheel, the operator can overlap the valve template with the sensor data that belongs to the steering wheel and use the turn affordance of the valve template as shown in Figure 8.

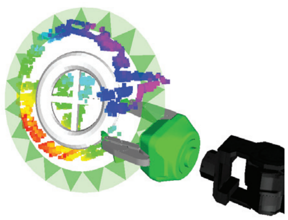
D. Blocked Door: Type 2

This experiment shows a task where the robot needs to open a door and walk through it. In this case the door has been blocked by a truss that fell in front of it as shown in Fig. 9. The truss is an overweighted tube structure which is difficult for the robot to lift. As humans would do, pushing or pulling a heavy object is a common manipulation motions for these cases which belong to class “txx” translation in one axis. A simple circular motion of the shoulder would not be sufficient due to the curved trajectory that the end effector would have, for this reason, a Cartesian path between the initial and final position of the end effector needs to be performed.

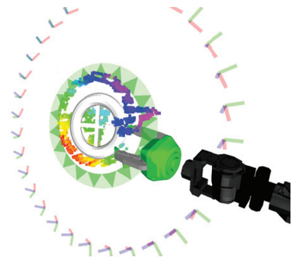
(a) Robot view of a steering wheel.



(b) Pointcloud of steering wheel.

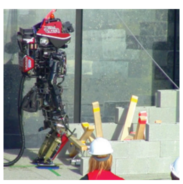


(c) Valve template overlapped with steering wheel pointcloud.

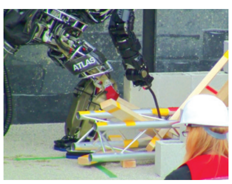


(d) Circular path of the wrist.

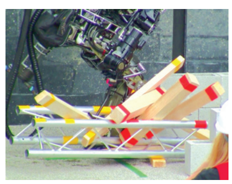
Fig. 8: The robot generating a circular path to turn the steering wheel with the right hand, but utilizing the "turning" affordance of a valve template.



(a) Robot and truss.



(b) Grabbing the truss.



(c) Truss being pulled.

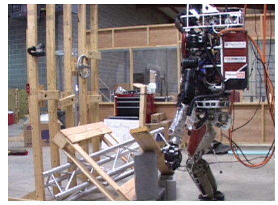
Fig. 9: A door blocked by a truss needs to be pulled away. Utilizing a translation affordance originally designed for an object with translation constraints (e.g. a drawer) can achieve the necessary manipulation motions to pull the truss in a direction parallel to the floor.

E. Unreachable Valve: Type 3

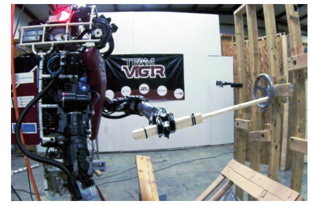
This experiment shows a situation where the robot needs to turn a valve, but in this case the valve is unreachable by the robot as shown in Fig. 10. The human supervisor then finds a wooden stick which can be used to reach the valve as shown in Fig. 10b. Since the affordances we designed are grasp agnostic, the operator can easily command the robot to generate a circular path to rotate the a stick around the axis of rotation of the valve. This experiment shows kinematic waypoints can be created on the fly regardless of the grasp pose with respect to the object and generate the same type of manipulation class required to accomplish the task.

V. CONCLUSIONS AND FUTURE WORK

We have presented a versatile manipulation approach for a supervised semi-autonomous humanoid robot to increase the potential of achieving manipulation tasks. This contribution extends a previous approach by incorporating the concept of manipulation versatility and formalizing how these manipulation skills can be transferred from known objects into new unknown objects on the fly. The ability to transfer manipulation knowledge between objects increases the potential to achieve a task by allowing the use of objects in new different ways as shown in Fig. 10 or the use of new unknown objects as shown in Fig. 8. We presented motivating examples which are by no means exhaustive, given the three example types for transferring manipulation skills one can think of different possible combinations.

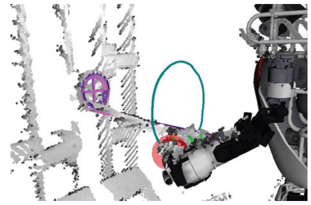


(a) Valve blocked by debris.



(b) Reaching valve with stick.

(c) Robot view from scene.



(d) Circular path of the hand.

Fig. 10: The robot using the "turning" affordance of a valve template but utilizing a stick to reach the valve. The circular path shown in (d) is calculated for the hand with respect to the valve axis of rotation and keeping the end-effector orientation. Video available as multimedia attachment.

Team ViGIR participated in the DRC Finals held in Pomona, California in the U.S. on June 2015. Available open source code is provided[3,4].

Ongoing work to improve our performance is focusing on automatic template fitting and tracking algorithms to increase the speed of our approach. Currently the definition of templates allows only to define affordances as constrained kinematic motion paths, but we would like to explore options for adding dynamic information, for example, expected forces needed for these motions.

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[3] https://github.com/team-vigir
[4] https://github.com/thor-mang

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