

# Acquisition of Basic Behaviors through Teleoperation using Robonaut

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## 1 Introduction

My area of research is in artificial intelligence and robotics. The major platform of this research is NASA's Robonaut. This humanoid robot is located at the Johnson Space Center. Prior to receiving this grant, I was able to spend two summers in Houston working with the Robonaut team, which is headed by Rob Ambrose. My work centered on teaching Robonaut to grasp a wrench based on data gathered as a human teleoperated the robot. I tried to make the procedure as general as possible so that many different motions could be taught using this method.

## 2 Work Accomplished

### Fall 2003

With this grant, I finally achieved this goal. Robonaut is now capable of grasping a wrench with fair reliability anywhere in its workspace.\* The completion of this goal allowed me to finish my Master's thesis [1] in December 2003. In addition to helping to pay for my tuition to Vanderbilt University's School of Engineering, this grant allowed me to visit Houston in September in order to perform the final experiment needed to show my findings. The following is an excerpt of a journal paper [2] that is based on my Master's thesis. This is extremely relevant because my PhD work is a continuation of this research. (The works referenced inside this quotation are listed at the end of the quote, not in the references section at the end of this document.)

#### I. INTRODUCTION

The paper deals with the problem of enabling a robot to learn from experience by building models of the dynamics of its own sensory and motor interactions with objects and tasks [1]. This interaction is initially provided by fine-grained teleoperator inputs. Over time, information gleaned from teleoperator guidance is compiled into autonomous behaviors so that the robot can perform tasks on its own and so that the level of discourse between operator and robot can become more abstract.

... if a robot is controlled through an environment to complete a task while recording its [sensory-motor coordination (SMC)] vector time-series, the result is a state-space

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\* As long as the wrench is positioned vertically. The inclusion of rotation angles is proving problematical, mainly because it is nonsensical to add a distance in centimeters to a distance in angles. This issue is one of the things my current research is attempting to address.

trajectory that is smooth during the execution of a behavior but that exhibits a corner or a jump during a change in behavior (an *SMC event*)....

This paper reports the results of learning to reach toward and grasp a vertically oriented object at an arbitrary location within the robot's workspace by superpositioning a set of SMC state space trajectories that were learned through teleoperation. The ideas behind the procedure are based on a number of assumptions:

- (1) When a teleoperator performs a task it is her/his SMC that is controlling the robot. So controlled, the robot's sensors detect its own internal states and those of the environment as it moves within it. Thus the robot can make its own associations between coincident motor actions and sensory features as it is teleoperated.
- (2) In repeating a task several times, a teleoperator will perform similar sequences of motor actions whose dynamics will depend on his/her perception of similar sensory events that occur in similar sequence. As a result, the robot will detect a similar set of SMC events during each trial. Therefore each trial can be partitioned into *SMC episodes*, demarcated by the common SMC events.
- (3) Sensory events that are salient to the task will occur in every trial; sensory signals that differ across trials are not significant for the task and can be ignored. By averaging the time-series for each episode point-wise over the trials, a canonical representation of the motor control sequence can be constructed. As a result of the averaging, true events in the sensory signals will be enhanced and those that are random will be suppressed....

### III. BEHAVIOR SUPERPOSITION

There were four phases in the data gathering and analysis for this learning task:

- 1) A teleoperator controlled the robot through the tasks that would serve as examples. Five trials at each of nine locations were performed of a reach and grasp of a vertically oriented object (a wrench). As the teleoperator performed these example motions, Robonaut's sensory data and motor command streams were sampled and recorded as a vector time-series or signal.
- 2) The SMC events common to all trials were found and used to partition the signal into episodes. The episodes were time-warped so that the  $j$ th episode in the  $k$ th trial had the same duration (and number of samples) as the  $j$ th episode in every other trial. (cf. Section III-C.)
- 3) The signals were averaged over all five trials at each location to produce a canonical, sensory-motor data, vector time-series for each location. ...
- 4) These generalized motions were combined using the process described by Rose et al. [22] called *Verbs and Adverbs*.

When the process completed, the resulting set of parameters could be saved to file and then used to create a general representation of the task that was adaptable under real-time conditions.

#### *A. Teleoperation*

The task performed by the teleoperator was to reach forward to a wrench affixed to a frame, grasp the wrench, hold it briefly, release it, and withdraw the arm. The frame made it possible to re-position the wrench as needed while keeping it steady during task performance. For the purposes of these experiments, the wrench was positioned in a reachable, nearly vertical position. Nine example locations were chosen. Eight of these were positioned approximately at the corners of a virtual box that defined the limits of the reachable workspace. The ninth was a point near the middle of the box. Five trials were repeated at each of the nine locations....

#### *B. Segmentation*

A vector time series ... was recorded during each teleoperated trial of the task. The time series contained [over 100] separate signals ... from the various sensors and actuators. ...

The time-series data from the experiment was manually segmented into 45 trials according to markers embedded in the voice channel of the robot's data stream. Then each trial was partitioned into five SMC episodes (reach, grasp, hold, release, withdraw) demarcated by SMC events that were found through an analysis of the mean-squared velocity (MSV) of the joint angles....

#### C. Time Warping: Normalization and Averaging

Once the segmentation of the data was complete, the SMC episodes that comprise the task were time-warped through resampling to have a duration equal to the average duration of the 45 trial episodes. Then for each of the 9 locations the average vector time-series was computed from the five corresponding trials. For example, the *reach* behavior averaged 150 time steps across the 45 trials. Each of the time-series that comprised the *reach* episodes was time-warped and resampled to have length 150. The five *reach* episodes from the five trials at each location were averaged to create nine exemplar *reach* episodes each with 150 samples in duration....

#### D. Superposition using Verbs and Adverbs

After the resampling and averaging of the sensory-motor data from the example tasks, the data were analyzed to characterize the motions that would enable Robonaut to reach toward and then grasp a vertically oriented wrench anywhere within its workspace. This was done with an interpolation method called *Verbs and Adverbs*, (VaV) developed in the computer graphics community by Rose et al. [22]....

In [22] several example motions were created for articulated characters. The mapping of these motions into a multidimensional adverb space defined extremal points along axes of the space. A particular adverb extremum characterized the appearance of the associated motion. To create motions that exhibited combinations of the characteristics, a location in the adverb space was selected and mapped back into the motion space. In the work described here, the adverbs are the 3D Cartesian world coordinates of the object to be grasped (the wrench). Exemplar reach-and-grasps were acquired near workspace extrema for the robot's right arm. To perform the operation at other locations in the workspace, the VaV algorithm was used to interpolate the exemplar motions....

### IV. EXPERIMENTAL METHODS AND PROCEDURES

The VaV procedure was tested in simulation and on Robonaut. Simulation tests were run on a randomized list of 269 reachable targets in a 3D grid that covered the entire workspace and extended somewhat beyond the edges defined by the original box. The test on Robonaut was performed by affixing a wrench to a jig, and placing it arbitrarily at reachable points in the workspace. Some attempt was made to cover the entire workspace, but since the goal was to prove that Robonaut could reach randomly generated targets, a systematic selection was not used....

### V. RESULTS

...The Verbs and Adverbs method ... had better than 99% accuracy in the simulator trials, which were designed to cover the entire workspace. While not performing perfectly in the physical trials, it still [successfully grasped the wrench in 20 of the 23 trials.]....

### REFERENCES

- [1] Peters, R. A., II, K. Kawamura, D. M. Wilkes, D. M. Gaines, R. O. Ambrose, "Robot learning and problem solving through teleoperation with application to human - robot teaming: a white paper", Center for Intelligent Systems, Vanderbilt University. Unpublished manuscript, Robot Learning White Paper 20001129.pdf, download from, <http://www.vuse.vanderbilt.edu/rap2/papers/>, November 2000.
- [22] Rose, C., M. Cohen, and B. Bodenheimer, "Verbs and Adverbs: Multidimensional Motion Interpolation", *IEEE Computer Graphics and Applications*, vol. 18, no. 5, pp. 32-40, Sept. 1998.

### **Spring 2004**

In the spring of 2004, having finished my Master's thesis, I started my PhD class work. Besides completing these classes, I spent the spring researching methods of data segmentation, as the method that I had used to segment the grasping data did not prove to be as general as I had hoped. I also spent some time looking into the problem of representing angles in such a way that the Verbs and Adverbs method would be able to teach Robonaut to grasp a wrench at any orientation. As yet, no reliable solution to either problem has been made. I'm using this year's renewal of my grant to continue to look into these issues.

### **Summer 2004**

In the summer of 2004, I went back to Houston for eight weeks. The research team there indicated that what they needed from me was to integrate my work with the work being done by several other institutions, especially UMass. Rob Platt, Andrew Fagg and several others (from UMass) were working on a way to let Robonaut use a power screwdriver to tighten lug nuts on a wheel. My work would be very helpful in the more freeform motions (getting the hand to the driver, and getting the grasped driver to the wheel, etc.) In addition to finding ways to integrate our work, I ended up taking on a level of my own research that I had been putting off.

In an ideal case, the robot should be able to identify a task and make a plan of actions that it knows that can accomplish that task. This plan would consist of a state machine that issues commands to various programs, such as the Verbs and Adverbs program or the program created by Rob Platt that used force sensors to grasp the driver. The very nature of a state machine is ideal for this purpose because it has, built into it, a way of handling contingencies. If one of the programs it calls fails to work (for whatever reason), that program can report a failure to the state machine, which can take a different branch and perform different behaviors than it would have if the program had succeeded. If the state machine could not recover from the failure, it would then report failure to the planning mechanism, which would make a new state machine based on the new situation.

While the level of planning is still out of reach, this summer proved that it was necessary to create the state machine program anyway. In this sense, the humans around the robot became its planning mechanism. This opened up wide doors for human-robot interaction. The end-result of the summer was a demonstration that was shown to representatives from DARPA, which was funding a great deal of the research. This demo involved a human pointing out the power screwdriver, wheel, and lug nuts to Robonaut, and indicating which order Robonaut was supposed to use when tightening the lug nuts. Robonaut would confirm its instructions, then reach for the driver, grasp it, then tighten each of the lug nuts in order. Of course, because this is real life, sometimes the lug nuts wouldn't be tighten all the way, but a set of complex contingencies both in the program that tightened the lug nuts and in the state machine allowed Robonaut to detect this error and retry several times, until the lug nut was tightened.<sup>†</sup>

In addition to the major step of creating the state machine and the work of gathering and hand-segmenting the new data that was required for Verbs and Adverbs to

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<sup>†</sup> If Robonaut failed several times in a row, it would ask a nearby human for help.

operate the demo (mainly this data consisted of numerous teleoperator examples of the demo described above: grasping a drill and tightening lug nuts), I spend a great deal of time on my own research into automatic segmentation methods and on ways of incorporating rotations into Verbs and Adverbs. However, the needs of the group superseded my own research, and I have not yet succeeded in finding the solutions to those very large problems.

### **3 Conclusion**

Overall, I would count this year a success, although in unexpected ways. I have achieved the goal of acquiring a Master's Degree. I have not found the method of segmentation or the method of incorporating rotations into Verbs and Adverbs that will make my teaching method truly general, but I have created the next stage of the overall intelligent system that will need that teaching method. Research is ongoing, as I am now in my second year of the GSRP grant, and intend to apply for a third.

### **References**

- [1] Campbell, C. L., *Learning through Teleoperation on Robonaut*, M. S. Thesis, Vanderbilt University, December 2003.
- [2] Campbell, C. L., R.A. Peters II, R. Bodenheimer, W.J. Bluethmann, E. Huber and R. Ambrose. "Superpositioning of Behaviors Learned through Teleoperation." *IEEE Transactions on Robotics* (to appear).