Final SBIR Proposal | Joshua Shapiro | 12 December 2016

**Project Summary**

The goal of the proposed project is to provide an algorithm that will provide robots with enhanced grasping capabilities. The algorithm will take in object features including material strength, temperature, center of gravity, and friction coefficients as well as a robotics arm configuration. Through the use of machine learning and simulation, a series of potential grasping positions will be generated that will allow a robot to safely and properly grasp and move the given object. Initial research and testing will be conducted using OpenRAVE simulation software with its grasping module, and the algorithm will be tested using Willow Garage's PR2 robot. As this project focuses on improving the dexterity and manipulation of robots, it falls under the subtopic RH2, Robotic Applications. Keywords released to the proposal include machine learning, OpenRAVE, robotic grasping, and human-robot interaction.

This Small Business Innovation Research Phase 1 project addresses the current issue of robotic grasping. As it stands now, objects as simple as a coffee cup prove challenging for robots. By using grasping algorithms of today, material properties of objects are lost. Grip strength has to be guessed and tested instead of calculated based on center of gravity and coefficients of friction. Whether the objects contain liquids or are made of fragile materials does not affect the grip output. When handling a coffee cup for example, the robot has no understanding that gripping the cup on its interior surfaces would contaminate an individual's coffee.

In the proposed approach, once the robot detects the object in question, it will look at precomputed grasping positions that the intelligent algorithm calculated. These positions will take into account the object's material, acknowledge there may be surfaces that cannot be grasped (such as the inside of a mug), and understand the best grip positions factoring in center of gravity and friction.

This project assumes that the object properties (center of gravity, coefficient of friction, surfaces that are off limits for grasping) are already determined and provided to the algorithm. The main focus of the project is to predict the best grasping position given this data, not fetching this data in the first place . The two largest hurdles to overcome will be understanding how all this data interacts as well as how to generalize a solution to a variety of different complex objects.

The project will begin with extending OpenRAVE's grasping module to work with complex objects in a physics free environment. After that the research will be focused on using the supplied data points to generalize a solution for any object. This algorithm will then be used to extend the grasping module. Once the algorithm has been run through a number of simulations, it will be tested using the PR2.

The success of this project will aid in the advancement of human-robot interaction. In the past 5 years, there has been great success with bringing robots into the home. Machines like the Roomba and Amazon Echo demonstrate the progress made in speech recognition and robot navigation. The last part of the puzzle needed for complete human-robot interaction in the home is the ability for a robot to interact with objects in its surroundings. By creating a grasping algorithm that takes into account the variables that come up in a typical home, this problem will become partially solved.

Commercially, this technology will provide the basis for the development and production of robots that can take care of the sick and elderly, help clean houses, and even take care of young children. The impacts of grasping are far reaching, and this technology will bring true human-robot interaction closer to the masses.

# Project Description

## Elevator Pitch

In the past 5 years, there has been great success with bringing robots into the home. Devices like Amazon Echo and Roomba illustrate the advances that have been made in natural language processing and indoor navigation. However, one piece of the puzzle is still absent before we can have true human-robot interaction in the home. That piece is grasping. The current algorithms for grasping do not work well for dynamic environments and typically do not take into account material properties of the objects being grasped. This limitation is fine for factory robots that work in a human-free environment manipulating the same object in the same way, but for robots to exist in the home a better solution must be found.

This proposed project aims to create that solution. By taking in material properties such as center of gravity, friction coefficients, and surface material, the proposed algorithm will be able to suggest better grasping positions for robots. This results in robots that could pick up coffee cups without spilling, handle tv remotes without accidentally pressing buttons, and moving cooking utensils while being cognizant of hot areas.

By creating an algorithm that enables robots to process not just objects but the context in which they exist, we will be one step closer to true robot assistants in the home. The elderly would be able to live at home with their independence. Those that are sick would still be able to have a proper home-cooked meal. While grasping seems like an insignificant problem, its solution will prove immensely beneficial to the future of robotics.

## Commercial Opportunity

In the United States there are over 12 million individuals who live in some form of assisted living. These people have lost their independence due to old age or chronic illness. Though not physically able, a large percentage of these individuals are completely mentally aware, and crave for the independent life they once had. They wither away in assisted living facilities, burdening family members with the high financial costs of care. Additionally, the care provided at these facilities varies drastically, and numerous reports of elderly abuse populate the news every year. It is sickening to realize individuals with their full mental faculties are being cast away and abused in costly nursing homes simply because of physical disabilities or age.

The problems that face adults in assisted living facilities also affect young children. 21 million people in the United States are under the age of 5. These children are incapable of taking care of themselves, and must be supervised throughout the day. For some families, this care takes the form of expensive nannies. For others, child care consists of daycares that suffer from similar problems as nursing homes. These facilities are typically over priced and understaffed, and in some cases employ unqualified workers that abuse the children. Even so, for other families daycare is simply too expensive and young children are left at home and neglected as the parents are forced to go to work. None of these situations are perfect, and these experiences in a child's formative years will shape the child for the rest of his or her life.

For both children and the physically disabled, there is an apparent need for robotic assistants. While the technology is at least 5 years out, it is not unreasonable to replace human care in both of these situations with robots. For the elderly and physically handicapped, a robot in the home could give back the independence that they once had. For children, a robot could provide the one on one attention that is not possible in a daycare setting. And for both of these groups, robots would be far cheaper in the long run than the other options and would provide more standardized non abusive care for all individuals.

Though robots will solve the various problems that plague the child-care and assisted-care industries, there are a handful of issues that keep this technology 5 years away. The current cost of a robot with the sensors necessary to navigate a home environment and interact with it is over $400,000. Given enough time, this cost will drop substantially, and research has been conducted in manufacturing parts in a far cheaper way. If a robot is to traverse an individual's home, it is imperative that it has the ability to navigate without GPS and can identify stairs and other obstacles that it cannot traverse. While this navigational skill is definitely a barrier to entry, devices like the Roomba show that it is possible to implement interior navigational capability in production. Most importantly, if a robot is to interact with humans it must be safe. There should be no way the robot can injure individuals or pets, and it is assumed the robot will not destroy its environment. Most factory robots work in controlled settings where humans are not present, so this is one area of research that will need to be expanded over the next 5 years. Finally, if a robot is to help those in need, it must have the capability to fetch objects and bring them to the user. This grasping capability is the focus of this NSF proposal.

Currently, basic grasping algorithms do exist. It is possible to objectively compute the "best" grasping positions given an object, however these algorithms do not take into effect the object's material properties. This type of algorithm works fine when robots are picking up screws and bolts to assemble cars, but falls short when a robot needs to fetch a tv remote or glass of water. In both of these circumstances it is imperative the robot knows more about the object than its shape. For the tv remote, the robot must not press buttons when picking it up. For the glass of water, the robot needs to understand that the glass may shatter if squeezed to hard, the interior of the glass is not a good place to pick it up, and the orientation must remain upright so as to not spill the water when moving. The proposed algorithm handles these situations. By taking in human input for the material properties of objects, a database is created that can be shared across multiple robots. Once a robot identifies an object, it can look in the database for the material properties and then generate a grasp with these new attributes in mind. Once completed, this algorithm will revolutionize human-robot interaction.

As stated above, it will take an estimated 5 years before a robot can replace humans in assisted living situations. A large part of this time is due to the stringent safety testing that would need to be conducted before a robot could be put into production. If this device were also responsible for administering medicine to patients, other tests would be required that could set back production by at least another 3 years. However, the grasping algorithm is no more than 1 year away from complete development. Since the fundamentals of grasping have already been completed and the code is being used today, the updated grasping algorithm simply requires extending the pre-existing code base. While some of the code will have to be modified and rewritten, the majority of the work will involve using object attributes to create a subset of the object. This subset can then be run through the original algorithm to generate possible grasps. The cost of grasping development will not be high, though the expenses for safety testing will be substantial.

While production of the robot will be expensive, the demand for the product ensures that a profit will be made. By just looking at the two customer segments mentioned in the beginning, 10% of the United States population can use this product. If the cost of the robot is $20,000, this will net a revenue of $660,000,000,000. Insurance could subsidize a large portion of cost allowing a greater market reach. Then, software updates and repairs ensure that there will be a continuous cash flow after the initial sale.

Even will high cost of testing, the revenue is promising. Over time, newer versions can be developed causing increase in sales, and eventually the market can expand to the wealthy. Overall, this product can revolutionize the world. Robots can give independence back to those who lost it too early in their lives. They can give children the individual attention needed at such a young age. Robots can solve some of the biggest problems in the assisted living industry, and by financing this algorithm we will be one step closer to this robot reality.

**Societal Impact**

As mentioned above, 33 million people in the United States are dependent on another human being for the most basic tasks. If left alone, these individuals would sadly perish in a matter of days. These individuals currently receive expensive and subpar care, and are in dire need of an alternative. The creation of robotic assistants can drastically reduce the cost of care while substantially increasing the attention given. Elderly individuals would no longer need to be put in nursing homes, and could keep their independence and live in their own houses. Children would no longer need to be taken to and from daycare, and could simply stay at home with the added safety of a robot. Just looking at these two customer segments, 10% of the United States population can be positively affected by the production of robot assistants.

In addition to those who truly need this technology, robot assistants could quickly expand to wealthy homes and to the workplace. The wealthy who hire butlers and maids could easily replace these individuals with robots that cost less and perform better. Workplaces could begin to replace some of the repetitive monotonous tasks with robots as well. Currently at Carnegie Mellon University there is a fleet of 6 robots that deliver mail and packages between classrooms. In a similar vein, offices could use robots to pick up mail, fetch copies from printers, and get coffee for the workers. This would yield higher productivity from the workforce as less time would have to be spent doing repetitive monotonous tasks and more time could be spent solving the creative challenging problems humans are good at solving.

Unfortunately, safety is a large concern regarding putting robotic assistants in production. The obvious fear is that robots may accidentally cause injury to humans or pets when navigating through home environments. While thousands of hours of safety testing will be performed on these devices before they are put in production, there are no clear laws or regulation that dictate how to test robots for human-robot interaction. Similar to the self-driving car problem, new rules would have to be created, and that is a time consuming process surrounded by rolls of bureaucratic red tape. Even with the laws in place and stringent safety tests performed, there is always the miniscule chance that something goes wrong. And when that eventually happens, the blame must be placed on someone. When a human makes a mistake at a nursing home or a daycare, it is evident who should take the blame. When a robot makes the mistake, is it the company's fault, or is it no one's fault at all? This question is one of many that need to be decided by lawmakers, and must be done before robots can be present in homes and the workforce.

On a broader scale, the addition of robots in the workforce would unfortunately force a large number of individuals out of their jobs. Those working in healthcare taking care of the elderly and physically disabled will be partially if not fully replaced by robots. Those running daycares will no longer be need either as children could stay at home with their robot. While the future may be grim for both of these professions, the transition will not be immediate and most likely will take decades to fully occur. Additionally, the medical profession will still need specialists to handle the most severe assisted living situations, and robots may not be best for all children. Though a large amount of jobs will inevitably be destroyed, a new industry will be created for manufacturing, servicing, and selling the robots. In the past similar problems have been faced when dealing with innovation. The advent of the car put thousands of horses and carriage drivers out of business, and automated farm equipment put thousands of day laborers out of work. Few would argue that it would be better to not implement the new technology and keep the old jobs. It is important to ease the transition to new innovations as much as possible, but job loss should never prevent innovation from occurring in the first place.

There are unfortunately some severe downsides to robotic assistants, however the good that can come of them far outweighs their negative impact. 33 million people's lives would be dramatically improved, and the amount of elder abuse and child abuse would plummet. Individuals would be able to live independently at home longer, and the number of people withering away in nursing homes would plummet. People would be happier, healthier, and safer, and this positive impact makes the development of robotic assistants worth it in the long run.

## Technical Discussion and R&D Plan

### Introduction

As explained above, the applications of this research has substantial risk and cost associated with bringing a product to market. Most of this risk and cost will be minimized as time passes, since production costs will decrease over time and greater safety testing can be performed. That being said, the applications are years away at best. When focusing solely on Phase 1 of this project -- simply the research proposed -- there is very little risk. The output of the proposal is simply a software simulation, incapable of any physical damage save for perhaps causing a computer to run hot. The highest risk that could occur is that there is not a market for the simulation, and the cost of developing the software cannot be recouped. With proper market research however, even this cost can be mitigated.

Though the cost and risk for this Phase 1 project is fairly low, there are many technical challenges. To fully understand these problems, the project proposed must be explained in much higher detail. In order to provide an easy way of understanding both what is required to complete the project and the challenges that will come up, the rest of this section is formatted as a timeline outlining the critical technical milestones that must be met, and how some of them have already been met. The milestones are organized by the order they should be completed, though some will occur at the same time since they are dependent upon each other. This is noted when the dates for the modules overlap each other.

### Research of Prior Art -- Week 1-3

The initial part of Phase 1 involves investigating the current methods of grasping and what software is used to solve this problem. This is important to establish a baseline both on performance and types of calculated grasps. By investigating the different types of software available for simulation and solving these problems, the aim is to discover which framework/simulation tool will make this project solvable with the least amount of time wasted on fixing bugs, reading poorly documented code, and emailing developers.

At this point there are two main technical hurdles outlined above. The first is attempting to find the "grasping baseline". There are thousands of papers dedicated on this topic, and hundreds more are being published each month. From the current papers available, there are many different ways to solve the grasping problem. Some attempt to use large databases of precomputed data to speed up performance while others simplify complex objects to limit the number of grasps that can be computed. Because of this, state-of-the-art grasping has no correct answer which makes finding a baseline challenging.

The second challenge is to discover the software that should be used to develop this proposal. This is perhaps one of the most important decisions to make for the entire project. This software will become the backbone of the final simulation software. It must provide all features necessary to implement a new grasping algorithm, have a large user base so that the final project can be accessed easily by a large market, have an active community that can provide help and documentation, have a well-documented code base, and provide maximum functionality with minimal effort to ensure the success of this project. Shockingly, even with all of these criteria there are multiple options for the software. On top of that, the papers from the first section use a variety of frameworks and software for their solutions, and each provide a variety of functionality.

By the end of this milestone, the decision was made to use OpenRAVE as the software and the baseline was the built-in grasping algorithm. OpenRAVE has a large user community and a lot of powerful features, though it is a complex software with poor documentation, a variety of unclear dependencies, and hides a lot of low level commands behind many layers of abstraction.

**Research of OpenRAVE & How it Works -- Week 4-10**

Once the decision was made to use OpenRAVE a deep read of the documentation and source code was necessary to understand how it works. At this step example code and small prototypes need to be tested and ran to understand the underlying framework. A good grasp on the overall design of OpenRAVE should come out of this.

The main technical hurdle in this section is to understand OpenRAVE's framework. There are hundreds of pages of documentation that all change depending on the version of OpenRAVE that is being used. Additionally, there are very few tutorial that exist on OpenRAVE, making learning the basics even harder.

By the end of this milestone, a basic understanding of how OpenRAVE handles environments and robot manipulation was learned. Problems were discovered with loading in objects, calling functions, and running example code, however all of these hurdles were overcome during this stage. It was also discovered OpenRAVE is written in C++ with a Python wrapper, which makes it harder than initially expected to trace through code and debug things.

**Establish Testing Harness -- Week 11-15**

After a basic understanding of OpenRAVE is obtained, a testing harness for grasping must be set up. This should take as input multiple objects, a grasping algorithm, and a robot. It should then test the grasping algorithm on all objects and provide a visual output. At this stage it is not necessary to return an "accuracy" measurement for how good a grasp is, but it should be able to show what the grasp looks like on a given object and show the list of grasps generated by the algorithm.

The technical hurdle with the above harness stems from OpenRAVE's complex architecture. Not only does this system have to take in different robots and multiple objects, it also has to show the act of grasping. While functions exist inside OpenRAVE to calculate the inverse kinematics necessary to move the robot to the correct position, threading problems occur and the program crashes. It is unclear what is causing this.

After investigating this task, some significant progress was made. A scene was created in which multiple robots could be placed, and multiple objects could be set on a table. As will most grasping robotic simulation, this scene has no physics associated with it. The built in grasping algorithm can then be called on this scene, causing the selected robot to generate grasps on specified objects.

Unfortunately, the visual output is not completely solved. After reading through documentation, going through code, and talking to experts in the field it is unclear what is causing the thread error that crashes the environment. It may in fact be a bug in OpenRAVE and therefore out of the scope of this project. To go around this issue, the test harness is able to visualize the robot hand in the grasping position instead of rendering the actual movement of the robot to the grasping position. As explained above, this testing harness should also be able to calculate the performance and accuracy of the grasp, though these are subcomponents that will be completed later.

**Establish Evaluation Metric for Grasps -- Week 15-18**

In addition to setting up a testing harness for grasping algorithms, there needs to be some way to compare grasps to each other. There will be multiple metrics that are part of this evaluation, and this section is used to identify these individual metrics. Obviously performance is one of the metrics to evaluate, and it will most likely be the easiest to measure. Simply looking at the runtime of each algorithm should be enough for this. Accuracy of a grasp, however, will be much harder to measure.

To discover the answer to this problem requires understanding what makes some objects harder to grasp than others, and this effectively could be a paper in and of itself. For this reason, the technical challenge to solve in this step is find a way to analyze the accuracy of a grasp without attempting to discover what makes some objects harder to grasp than others.

Though this problem has not been solved yet, one of the approaches that will be investigated is to do a case study with a random sample of humans picking up a subset of objects. This assumes that humans grasp objects in the best way possible, which may not be true. However, the way humans grasp objects clearly work, so this should provide some baseline that the grasps generated by the algorithms can be measured against. Additionally, other papers will need to be studied to determine how others measure the accuracy of grasps.

**Analyze Built-In Grasping Algorithm -- Week 16-19**

Before creating the human assisted grasping algorithm, it is necessary to fully understand how the chosen baseline works. This requires going through OpenRAVE's grasping database code line by line to understand exactly how it is working. While it may seem simple to go through the code, OpenRAVE makes this a bit more challenging than it should be. Because there is a Python wrapper on C++ code, it is unclear if the entire grasping module has been written in Python, or if there are sub calls to other precompiled files. Additionally, though going through the code will provide a very detailed explanation of how the grasping algorithm works, it may not provide a good explanation for a high level view of the algorithm.

Not much work has been done on this module yet. There is little documentation on the built in grasping code, but links have been found that provide a high level overview of the algorithm. By looking at the high level view, it is clear where some improvements can be made that should increase accuracy of grasps. Additionally the separate modules of the grasping algorithm have been located. Doing a deep dive on the code has not been completed yet, but should illuminate exactly how the algorithm is working. This will be crucial for the next objective of the Phase 1 project.

**Decide on Extending or Rebuilding -- Week 20**

After the built in grasping algorithm has been analyzed, an important decision must be made. To create the human assisted grasping algorithm, there are two paths forward. First, it could be written from scratch, recreating each portion of the built in grasping algorithm. This involves creating a module to analyze the object, a module to generate grasps based on the analysis, and a module to rank the generated grasps. The second option is simply to extend and modify the current built in algorithm. This would effectively involve modifying small portions of each module or changing the input object's surface so that the default grasping algorithm has significantly better performance and accuracy.

Choosing one of these two options will be challenging and will dictate a large portion of the final product. While extending will most likely be easiest, it may not provide the flexibility necessary to have the desired increase in performance and accuracy. On the other hand, while writing everything from scratch provides the necessary flexibility and will make reading in human input easier, it may make it impossible or very challenging to integrate the algorithm with OpenRAVE. This is extremely important, since integration with OpenRAVE is imperative to distribute the product to its consumers.

At this stage research will also have to be completed on algorithmic strategies for the final product. The decision to use machine learning, some form of simulated annealing, or a variety of state space search techniques will need to be investigated. By choosing the type of algorithm to use for human assisted robotic grasping, the question to extend or rebuild the grasping module may be already answered.

**Create Custom Algorithm & Evaluate -- Week 21-25**

Once an algorithm has been chosen and the decision to extend or rebuild OpenRAVE's grasping module has been made, the work to write the custom algorithm must begin. This will include figuring out how to read input from a human (for the human assisted part of grasping), as well as how to integrate the information provided to influence the grasps produced. Of course, how this information is integrated will depend on what type of algorithm is used (machine learning vs state space search vs object manipulation).

After the algorithm has been created, it will need to be tested using the testing harness created in previous modules. A specific set of objects must be chosen for training and validation to tune the algorithm and its parameters, and a different unseen set must be used for evaluation purposes. At this point it should be possible to do an apples to apples comparison of the human assisted robotic grasping algorithm to the built in OpenRAVE grasping algorithm. As long as there is substantial improvement, Phase 1 will be completed at this point and the project will be completed.

Some small changes may need to be made to polish the custom algorithm into a finished product, but by the end of this step the goal of Phase 1 will have been met. A grasping algorithm that uses human assistance will have been created, and it will perform better than the built in module that it is tested against. With an additional 5 years of research, it is possible to integrate this software into a commercial product that could truly benefit thousands of individuals lives.

## Revisions

Due to the very brief time allotted in class for peer reviews, my reviewer was unfortunately unable to read my entire paper. That being said, the few comments and and criticisms provided were insightful. The main comment provided was that some sections seemed wordy. I did my best to read through sections and prune words that seemed unnecessary. Additionally, the reviewer suggested expanding contractions to sound more professional. I completely agreed with both of these comments, and made the necessary changes. The reviewer made no comments regarding structure or content of the proposal, so I did not change anything in that regard.