Simulation of Robotic Assembly Systems with NIST Pegboard Experiments

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Contents

1 Executive Summary

In the long run, industrial robot automation is seen as cost-effective and worthwhile, but the initial capital outlay can be daunting. Robotic equipment can conservatively[1] cost $50K (U.S. Dollars) for a serviceable 6-axis robot; peripherals, such as a gripper or force/torque sensor, can cost upwards of $10K (U.S. Dollars) apiece; then there can be special utility requirements such as power and pneumatic air to operate the robot and gripper; and then one must consider allotting for the space required and potential equipment to meet safety standards. The expected capital outlay can be considerable, making research and implementation of a robotic peg-in-hole assembly a costly proposition.

For evaluating a robot assembly operation, realistic simulation could offer a cost-effective alternative to physically modeling and assessing the performance of a robot in performing the assembly task. However, it can depend on the purpose of the simulation - is it to validate the logistics and understand the performance indicators impacting the design, or instead is it a physics-based simulation required to learn, understand, and model a complex manipulation operation. In this paper we discuss the use of a physics-based simulation to provide valuable insight into a robotic assembly application as if it were operating in a dynamical real-world environment. Indeed, considering all the cost and logistical requirements, a robot simulation offers a promising option for studying a robot application but only if one assumes a straightforward, expedient, and accurate simulation.

The peg-in-hole insertion operation is common task in robotic assembly research. In the real-world, robot positioning of a peg into the hole presents a formidable challenge due to the uncertainty of the assembly environment, the inaccuracies of the robot, and possibly the requirement for very tight tolerances. Clearly, simulation of the real-world assembly operation is not simple nor straightforward. The advent of software physics engines allows simulation to actually incorporate gravity, friction, inertia, collision, and contacts as part of the simulation world. An accurate physics engine is a mandatory requirement in a simulated assembly operation since the peg, the hole sides and/or the support containing the array of holes can come in contact and require an accurate mathematical description of the forces indicating the direction of the contact. Without sensor feedback describing the contacts and forces between peg and various goal surfaces, simulated robot peg-in-hole assembly with tight tolerances is difficult.

This technical report includes a case study in the use of open-source simulation and robot control packages to model a peg-in-hole assembly simulation. The peg-in-hole simulation uses the NIST "pegboard" a CAD model of pegs (round and square pegs) as well as a platform of even-spaced holes in which to insert the pegs. The case study uses the combination of Robot Operating System (ROS), and Gazebo software tools to simulate robot peg-in-hole assembly. For Gazebo, we used the Open Dynamics Engine (ODE) physics engine a now antiquated but groundbreaking model of the physics of the simulated environment. Gazebo also provides a "plugin" that simulates a force/torque (F/T) sensor between joint 6 and the end-effector which can detect and report contact forces between the insertion peg and a surface (either the hole side or hole platform). Using Gazebo to determine the peg forces, the robot adapts motion based on these simulated F/T sensor readings and offers an exciting learning opportunity. The simulation uses the existing Agility Performance of Robotics System (APRS) laboratory Gazebo simulation [1,2] but replaced the kitting trays with pegboards. The Gazebo simulation world used a Fanuc

[1] Year 2022 Dollars

robot with a parallel finger gripper, one pegboard to contain pegs to insert, and another pegboard with empty peg holes that serves as a destination for the peg insertion.

It must be noted that in general any physics-based simulation will not suffer from degradation of equipment performance or deformation due to thermal errors, so a simulation can easily do the peg-in-hole assembly with dead reckoning every time. National Academy of Sciences held a workshop on Opportunities, Challenges, and Suggestions on the use of simulation in robotics which noted that many source of uncertainties are now only marginally handled in simulation [3]. Such issues in real-world that mar robot operation include friction, impact, contact, actuator noise, wear and tear, uncertain external loads, complex and unstructured environments, etc. For simulation to be valuable, the sources of uncertainty must also be present in the simulated world.

Thus, in order to replicate the difficulty of peg-in-hole assembly, errors must be modeled to more closely replicate the real-world. For instance, given a simulated peg-in-hole operation, the explicit random miss of the hole location and then performing a spiral search to find the hole by understanding a loss of contact reflected in the F/T sensor reading is a more realistic approximation to the real-world. Thus, F/T hole searching algorithms and insertion strategies, coupled with simulated approach errors, must be studied to effectively evaluate peg-in-hole simulation.

Overall, the aim of the peg-in-hole research is to use the theoretical aspects of part mating (e.g. forces, moments, etc.) to develop a practical simulation that deal with the expected equipment and algorithms used (e.g. robot, simulation, F/T, controller program etc.). Included in the report are some detailed procedures that were taken during development of the simulation case study. For example, all the Computer Aided Design (CAD) models were exported to Standard Tessellation Language (STL) for inclusion in Gazebo but had their centroid modified to exhibit a centered xy position around zero with minimum Z of zero. [others: ROS 1 noetic implementation on windows]

Keywords: robots, assembly, peg-in-hole, simulation, force control

2 Disclaimer

Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

3 Nomenclature

AI	Artificial Intelligence
API	Application Programming Interface
APRS	Agility Performance of Robotic Systems
CAD	Computer Aided Design
COG	Center of Gravity
COLLADA	COLLAborative Design Activity
CRCL	Canonical Robot Command Language
CRPI	Collaborative Robot Programming Interface
DARPA	Defense Advanced Research Projects Agency
DES	Discrete Event Simulation
F/T	Force Torque
IA	Intelligent Agent
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
KDL	Kinematics and Dynamics Library
KPI	Key Performance Indicators
LCPs	linear complementarity problems
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
ODE	Open Dynamics Engine
OROCOS	Open Robot Control Software
OSRF	Open Source Robotics Foundation
PID	proportional-integral-derivative
RCS	Real-time Control System
ROS	Robot Operating System
ROS-I	Robot Operating System Industrial
SRDF	Semantic Robot Description Format
STL	Standard Tessellation Language
URI	Uniform Resource Identifier
URDF	Unified Robot Description Format
WSL	Windows Subsystem for Linux

Pics/taskboardiros2020disassem.png

(a) Taskboard Disassembled

Pics/taskboardiros2020assembled.png

(b) Taskboard Assembled

Pics/taskboardtable1.png

(c) Taskboard Part List

Pics/taskboardtable2.png

(d) Taskboard Part List continued

Figure 1: Example Taskboard with Fastening Components

4 Background

NIST has developed several "taskboard" artifacts that replicate small part insertion and fastening operations found in manufacturing [4]. Figure 1 shows a representative taskboard, (disassembled (Figure 1a), assembled (Figure 1b), and a part list (Figures 1c and 1d). The taskboard employs various fasteners and fastening operations used in manufacturing assembly such as push-pin, threading, snap fitting, and meshing with standard screws, nuts, washers, gears, electrical connectors, belt drives, and wiring. Taskboards were designed to support evaluation of robotic assembly and disassembly operations, thus providing a standardized benchmark for comparative robot assembly performance evaluation. For example, a cheaper robot may perform adequately for simple push-pin insertion, while a more expensive robot may be required to do a connector fitting. Overall, taskboards help advance the development and deployment of robotic systems to support assembly operations and provide a performance measurement mechanism to differentiate capabilities. The NIST taskboard benchmark tools are used to test and evaluate real-world robot control systems. In fact, numerous competitions have been held to demonstrate and measure robot skill at assembly [5–7]. Interested readers can find additional taskboard guidance and supporting artifact designs online [8].

Part of the taskboard research has found that the most prevalent operation in assembly is insertions, accounting for over 35% of all assembly operations [9]. Recently, NIST has developed a CAD model of a "pegboard" that is another taskboard whose primary focus is to enable, challenge, and measure the simulation of peg-in-hole insertion. This technical report is interested in insertions, specifically, simulated force control insertion of a peg-in-hole assembly using NIST pegboard. An existing base of research can be found that support peg-in-the hole assembly where the primary goal was to analyze the force signature resulting from a robot control implementation.

This research studies the peg-in-hole problem where force characteristics of control algorithms are evaluated along with the success of the insertion [10–12].

Simulation has proven to be valuable for evaluating manufacturing. Manufacturing shops typically measure performance using key performance indicators (KPI). Discrete Event Simulation (DES) [13–15] is often used to model the manufacturing system's behavior and provides an effective performance analysis tool - either visually, statistically, or pragmatically. Thus, for example, in a manufacturing transfer line you can determine KPIs, such as the expected throughput or the station that is the bottleneck. Of note, if the estimated parameters for the simulation are flawed, then the simulation will be equally flawed. The requirement for good data, sound underlying mathematical science, and an accurate model of the simulated world is paramount to a useful simulation.

Overall, in simulation as well as the real-world system, the command and control software is evaluated to see how it responds to the challenges. These challenges can be continuous (such as a human entering a workzone and causing a work flow pause until the human is out of the workzone) or discrete (such as sensing a bad part). Indeed, many of the challenges are not explicitly problems, but rather system responsibilities that test the system for its agility [16–18]. Robot agility is defined as "the ability of a robot system to succeed in an environment of continuous and unpredictable change by reacting efficiently and effectively to changing factors" [19]. Systems that react poorly to agility challenges end up treating the challenge as a fault or worse, ignore the challenge and render a catastrophic outcome.

All manufacturing simulation is not exclusively for the measurement and analysis of shop-floor KPI. There are significant differences in the types and purposes of manufacturing simulations. We will distinguish between two simulation purposes for clarification of our research: logistical and physics-based simulation.

Logistical simulation is commonly used to analyze the shop-floor workflow behavior between multiple manufacturing stations in order to predict throughput, bottlenecks, starvation or other process indicators. These simulated workflows are based on previous observations or new estimates of system behavior such as Mean Time Between Failure (MTBF), Estimated Time to Completion, Buffer Size, etc.

Physics-based simulation is an extension to logistical simulation that exhibits real-world simulated elements. Now, MTBF is not just a performance simulation statistic, but the embodiment of a real-world problem. Physics-based simulation creates an ideal proving ground for developing robot applications that can both identify and correct mistakes and be verifiable. Physics-based simulation allows high-fidelity and flexible testing methods that magnify the differences between models and real-world conditions that may not be apparent in a focused results-driven real-world robot experiments [**?**]. Further, physics-based simulation provides a coordinated testing environment well-suited to the complex interactions between robots, sensors, and world model, and the effects of asynchronous and distributed execution on sensing and control.

Today, there are a number of physics-based simulators available and Liu and Negrut provide a a summary of various simulations tools, technologies, and specialties [20]. Game related entries include Unity and Unreal Engine . NVIDIA's GPU implementation is Isaac, which is offers Virtual world support using Unreal, and embeds PhysX for physics-based simulation. Finally, Gazebo is an open-source 3D physics-based simulator that can be used to design a virtual industrial robot world among other robotic endeavors.

We concentrate on Gazebo because although separate technologies there is a close integration with ROS.Gazebo is managed by Open Source Robotics Foundation (OSRF). Likewise, OSRF manages ROS, however the projects are managed separately and Gazebo is not a "part of" ROS. However, Gazebo and ROS integrate nicely, and a set of ROS API's known as the gazebo_ros_api provide users with a standard means to modify and get information from the simulated world.

In all, Gazebo is an open-source 3D physics-based simulator that can be used to design a virtual industrial robot world. Gazebo has been used for several robotics challenges, including the DARPA Robotics Challenge [21], Virtual RobotX [22], ARIAC [23] and Space Robotics Challenge [24].

Understandably, simulation versus real-world peg-in-hole assembly have different programming requirements. Real-world peg-in-hole must work to solve the application task while accounting for any expected or unexpected difficulties. In this case, there are random errors and unexpected challenges in the real-world that may be hard to simulate. For example, in the real-world equipment wear and thermal expansion errors can alter the precision of the robot as it attempts to insert the peg into the hole.

By contrast, a simulation model, such as physics-based one, requires a workable accurate model of the real-world elements. For example, the simulation model must account for the robots, sensors, world model, possible errors, potential challenges as well as the task at hand. For peg-in-hole insertion, a simulation using a physics-based engine handles the complex modeling. Now gravity, forces, contact, collision, and other dynamical physics properties that are inherently part of the real-world are modeled by the simulation physics engine. To be worthwhile, a simulation must account for all the aspects that are important to the real-world application. As mentioned, a dead-reckoning peg-in-hole insertion is not hard in simulation, but offers minimal value to validation of a real-world application. Further, often simulation is a two-step operation - first building the simulation of an error and then testing the simulated system against the error.

In addition to workflow problems, physics-based simulation will highlight real operation issues. Given a robot for example, we are concerned both with the logistical performance indicators of the robot, as well the physics-based actions of the robot so that motion problems such as overshoot or collisions can be determined before not after deployment. For peg-in-the-hole simulation, physics-based modeling is imperative otherwise the operation can be accomplished with an open-loop insertion, requiring no feedback for contact, forces or collisions. The lack of physics modeling simplifies the programming but makes it infeasible for representing and understanding real-world operation.

In this paper, we investigate physics-based simulation of robot peg-hole-assembly injecting various errors and exploring various peg-in-hole search techniques. To understand the peg-in-hole simulation in operation, a case study using NIST pegboard and Gazebo simulation is developed. The pegboard and peg-in-hole insertion leverages existing work from the NIST Agility Performance of Robotics System (APRS) laboratory. The APRS laboratory contains two industrial robots, a Fanuc LR-Mate 200iD and a Motoman SIA20F.. Software development relied on the open-source frameworks Robot Operating System (ROS) and Gazebo for robot control and simulation. In conjunction with APRS, in-house software development was leveraged to use existing Gazebo/ROS graphical physics and sensor based simulation of the in-house APRS agility lab [1]. We used the Gazebo ODE physics-based engine to simulate such that the models of the robots, kits, and environment provide a higher-fidelity approximation to the real-world.

This report is organized as follows. First, a background on NIST taskboards will be presented to better understand the rationale behind performance measurement of robot manipulation skill as applied to assembly operations. Included is a discussion on the importance and types of simulation that will studied using the NIST pegboard. Next, we will introduce the NIST pegboard including the components, names, various setups, and challenges in measuring manipulation and reasoning. Included in the pegboard discussion will be a review of the transformation issues of porting pegboard CAD models into Gazebo simulation modeling so that the pegboard behaves as one would expect. A simulated peg in the hole case study using the NIST pegboard will be developed that discusses the major software components of the simulation, including Gazebo simulation, ROS robot command and control, peg Grasping, and the Collaborative Robot Programming Interface (CRPI) assembly micro-motion primitives. Next a series of simulation experiments will be presented (some still software development). The basic peg-in-hole task will be described followed by a series of experiments The first experiment establishes the ability to use the Gazebo F/T sensor on the wrist to record the F/T values as the peg collides with a solid surface. The next experiment uses dead reckoning to establish the capability to acquire a peg, transfer the peg above an open hole, and then insert the peg into the empty hole. Within the dead reckoning insertion, the F/T values were recorded when the peg is re-positioned from a perpendicular insertion to an increasing non-perpendicular angle while inside the hole. The next experiment under development is to "wiggle" a peg that is stuck inside a hole. The final experiment that is also under development is to miss the hole and then use various CRPI micro-motions to find the hole using F/T analysis. Following the experiments, we discuss the positives of robot assembly simulation as well as challenges encountered during the robot assembly simulation. Included in the report are appendices that offer a deep dive on implementation and development caveats that may prevent operation of the robot assembly software. First, These appendices include discussion onthe repository, implementation using ROS on Windows, instructions for building and running the software hosted on github. One appendix is dedicated to instructing users on the deployment tricks required to get the Gazebo Robot F/T Sensor Plugin operational. Another appendix covers the details used to transform the exported CAD pegboard models as STL meshes into operational Gazebo pegboard models.

5 Related Work

Peg-in-hole is one of the most common operations in manufacturing assembly [25]. However, peg-in-hole, which is extremely trivial for any human [26], is challenging for a robot. Humans can easily recognize and orient the position of the assembly parts, and then mate parts by touch. In the case of robots, sight can be replaced by vision sensors and touch by force/torque (F/T) sensors. However, this is far from a simple substitution.

Over the years there has been a significant amount of research into the robot peg-in-hole assembly operation. In fact, mating a peg into a hole can be considered as one of the most classic problems in robotics. In the 1970s Nevins and Whitney [9] divided programmable robot assembly research into two research parts: how parts interact or part-mating sciences, and the union of part-mating processes forming a system that assembles products.

There is a wealth of robotic assembly strategies, of which these references are not exhaustive, but rather illustrate the wealth, and difficulty of the research. A variety of research solutions attempt to solve the peg-in-hole assembly challenge, such as the position-controlled assembly, passive compliance and various active compliance techniques such as force-controlled assembly [27–31]. One of the issues with the peg-in-hole research is the list of assumptions regarding the assembly task. For example, many research solutions assume a cylindrical peg and a slightly enlarged cylindrical hole or chamfered hole. As such, since the research requirements are often too lax and not amenable to actual production, precision robotic assembly has become a major research and industrial focus.

In the ideal case, a robot peg-in-hole assembly operation can be performed based on pure position control if accurate position of the relevant object (i.e., the hole) is provided and the position control error of the robot is small. However, difficulties associated with the inherent robot and object errors make position-control robot assembly difficult. However, if tolerances are loose, and the manufacturing process is very precise, robot assembly is attainable and rote programmable insertion is viable. For example, circuit board chip assembly is common position control insertion [32]. However, in general issues arise from inaccuracies using position-control insertion with a robot in an imprecise environment.

Whitney [27] went on to publish a part-mating approach with the idea of passive compliance to do the assembly. Trong et al. [33] present a general assembly model to understand dynamic insertion and the development of passive compliant devices capable of avoiding wedging and jamming in high speed assembly operation where they look at different factors influencing the behaviour of assembly processes such as: gravity, inertia, dry friction, compliance and insertion speed. Haskiya et al. present a passive compliance mechanism developed for robotic peg-in-hole assembly operations that can accommodate positional errors between the mating parts without a chamfer on either part [34].

There are many active areas of research studying the performance of F/T hardware in active compliance control. Sadun et al. [35] highlights a summary of currently related works on active compliant control by using the force control and the impedance control Active compliance control was used to improve the stability of multi-fingered robot hand by the measurement of disturbance with concern related to location of the contact points [36]. Active compliance control was studied by utilizing F/T sensor on the fingertips of the gripper [37]. Hybrid approach using active compliance and F/T sensing is found in research that studied robot hand grasping with a contact-rich fingers placement strategy for typical small objects such as pens, screwdrivers, cellphones, and hammers [38].

Many realistic robot assembly solutions have been researched. Stolt et al. [39] describes the assembly of an emergency switch which is snapped into place and detects the end of the operation snap using force sensing. Kleinmann et al. [40] propose a sensor-based, three-finger gripper approach that divides the mating process in three parts: part and hole identification, selection of correct insertion strategy, and handling insertion by means of five state classifications: movable, tilted, jammed, attached, and inserted. Shirinzadeh et al. presented a comprehensive study of robot-based cylindrical peg-in-hole tasks [41].

Since peg-in-hole is a classic research topic, research into machine learning to solve robot assembly tasks offers a challenging problem. Sharma et al. [28] presented peg insertion research using a neural network among several intelligent strategies that is trained to infer the hole center. Beltran-Hernandez et al. [42] investigate reinforcement learning-based method to solve peg-in-hole tasks with hole-position uncertainty. Schoettler et al. [43] consider a variety of difficult industrial insertion tasks using reinforcement learning with visual inputs and different natural reward specifications, namely sparse rewards and goal images.

Todo: DISCUSS SIMULATION OF PEG IN HOLE EFFORTS-MORE

Setchi et al. [44] have suggested a 3D simulation program for the peg-in-hole insertion process. This approach considers the insertion process as a sequence of discrete events, and models the process as a transition from one contact situation to another.

Overall, the relevant literature views peg-in-hole as various combination of processes:

- approach, edge crossing, one-point contact, and two-point contact
- two phases with search phase and insertion phase
- lowering, displacement, shaking, hole-search, and lifting

6 Pegboard Artifact

The intent of the NIST pegboard is to challenge robots to demonstrate assembly manipulation and reasoning skills. Assembly manipulation is demonstrated by the insertion of round or square pegs into a corresponding round or square hole. Reasoning at this basic level requires that a round peg be inserted into a round hole. This "part mating" [9] reasoning can range in sophistication. Peg and hole part mating can range from a dynamically sensor-based analysis of the assembly scene to a hard-coded data model of the entire pegboard world. Since physics-based simulation is the goal, the demonstration of peg insertion of a known peg type and location into a known peg hole type and location is sufficiently challenging as a starting point. As part of the research, we explore the use of simulated force/torque based sensing and its effect on motion control. Even insertion of a peg into a hole with known insertion types and hole locations can be challenging.

Historically, tolerances for the NIST taskboard given closely-assembled parts have been made looser than what might typically be used in an industrial assembly application. This is on purpose. These tolerances were chosen in order to facilitate difficult benchmarking tasks that pushed robot performance without being impossible or impractical to perform given current technological capabilities.

By contrast, the research in this report is about understanding the capabilities and limitations of simulation to handle robot peg-in-hole assembly by understanding the interaction of motion control and simulated F/T sensors. Using the pegboard as an assembly artifact, we investigate simulated variations on position, and active compliance using force sensing peg-in-hole strategies. Further, to effect more realistic simulation, we explore interesting peg-in-hole anomalies, such as deliberately missing the peg hole and then using a series of F/T hole seeking search algorithms to find the hole.

Sensing is vital to robot assembly. Sensors can be used to monitor and control the process, to provide a some adaptability for programmed deviations, and to improve motion control of the robot. Further, sensing can provide flexibility through the ability to perceive different parts, part mating types (e.g., hole, fitting) and can enable more flexible assembly of different part mating. For our research purposes, we assume simulation of the peg-in-hole insertion without simulated vision sensing to derive many of the pegboard object properties. Instead we focus on the role of the F/T sensor in the simulation. We will assume the simulation engine will dynamically supply the name and current pose of all uniquely defined objects, but not subfeatures of these objects. We call this a virtual sensor because it supplies the basic object knowledge that would require complex sensor fusion so instead we use the simulation engine dynamic world model knowledge. Further, although important dynamic pegboard knowledge will be supplied by a virtual sensor, much static knowledge will be explicitly modeled by the software. This is especially true in regard to subfeatures of an object. Static pegboard design factors include size, shape, hole location, and type of pegs and board arrays. It should be noted, that many of these object features (such as hole location) could be determined using the virtual sensor (i.e., the simulation world model), but often with significant programming difficulty that is not in scope of the main goal of the research, which is to simulate force-based peg-in-hole insertion.

6.1 Pegboard CAD Models

Figure 2a shows the Solid Works single pegboard design, which consists of five round and five square pegs, one pegboard BASE ARRAY, and one pegboard PEG ARRAY. Each pegboard object is designed in Solid Works and then exported as STL for use in Gazebo. The pegboards contain a grid of holes with alternating round or square holes. Under the hole grid, are tiered rows that successively climbs like steps in a staircase. As pegs are stored in the tiered holes, the grasping area of the peg top increases as the tiers underneath climb.

Pics/BinPickingPuzzledisassembled.jpg

(a) Single Pegboard

Pics/BinPickingPuzzledouble.jpg

(b) Stacked Pegboard

Figure 2: Different Configurations of Pegboard

Pics/Array_base_side.JPG

(a) BASE ARRAY

Pics/peg_array_1.JPG

(b) PEG ARRAY

Pics/SquarePeg.jpg

(c) Square Peg

Pics/RoundPeg.jpg

(d) ROUND PEG

Figure 3: Pegboard Elements

The pegboards can be combined to have more complicated reasoning challenges. Figure 2b shows a Solid Works visualization of a stacked pair of NIST pegboards. The stacked pegboards form a 90° angle between the "flat" and "upright" pegboards. The stacked pegboard setup presents obstructed access to some of the lower row of pegs on the upright pegboard. Thus, some advanced reasoning about collision avoidance and peg accessibility would be involved in unloading and loading pegs in stacked pegboards.

For clarity, we will illustrate and name each object that is part of the pegboard CAD models. Note, we use the term array to distinguish it from board and any confusiong with pegboard. A single pegboard consists of the following:

- BASE ARRAY- Figure 3a shows the base array with rising tiers that has groove for holding a peg array.
- PEG ARRAY- Figure 3b is the array that contains the round and square holes from which hole subfeature offsets are computed. A PEG ARRAY fits on top of the slots of a BASE ARRAY.
- SQUARE PEG - Figure 3c is the SQUARE PEG with flat beveled ends.
- ROUND PEG - Figure 3d is the ROUND PEG with flat beveled ends.

A few design and simulation observations are in order.

1. The pegs have a chamfer on the ends that helps center the peg within the hole during insertion experiments. However, the pegboard does not incorporate a chamfer along the rim of the hole. In general, a chamfer makes insertion in the real-world simpler as the chamfer "guides" the peg into the hole.
2. Assembly tolerances are an important consideration in peg-in-hole assembly. Tolerance is specified in the manufacturing process based part geometry, material type, and other specifications. Since tolerance in manufacturing is critical both for product quality, expected performance, and manufacturing cost, simulation should be verified by various tolerances - both tight and looser. Since changing the widths of the pegs is not difficult and can be done with a scale transformation, tolerances can be easily adjusted for different peg-in-hole experiments.
3. Orientation challenges are minimized as the mating of the round and square pegs to round and square holes requires no or minimal peg reorienting. Clearly part mating of complex shape geometries may be more difficult but are out of scope.
4. The pegboard pegs require no special grasping technology, and we use a two finger parallel gripper. Further, we assume a centered grasping the peg, and no additional reasoning concerning where to grasp on the object, how much force to apply to grasp, or any speed requirements when moving the pegs.

6.2 Pegboard CAD object models in Gazebo STL

The CAD simulation pegboard models do not necessarily have an equivalent representation of an object. For the simulated Gazebo world used, objects are expected to supply either an STL or COLLAborative Design Activity (COLLADA) [45] visualization mesh file, inertial frame, and a collision shape typically matching the visualisation. Other Gazebo model properties are possible to define but were not addressed in this simulation.

The pegboard objects model outlined above are more formally defined in the Gazebo model database [46] using SDF (Simulation Description Format). SDF is an XML format that describes Gazebo models and environments for robot simulations, visualization, and control [47]. An SDF model embeds a top-level <model> SDF tag, and is essentially a collection of links, joints, collision objects, visuals, and plugins. The <visual> XML element is used to visualize parts of a link. A link may contain 0 or more visual elements. The <collision> XML element encapsulates a geometry that is used for link collision checking. The <inertial> element describes the dynamic properties of the link, such as mass and rotational inertia matrix. A <joint> connects two links – one a parent and the other a child link – along with other parameters such as axis of rotation, and joint limits.

Gazebo is best programmed and understood using a standardized centroid that has a Cartesian xy value that is midpoint of the length/width values and a Cartesian z value that is at the bottom of the object so that it sits flat on a surface when placed in a Gazebo world. Thus, the first modeling requirement for Gazebo simulation using the NIST pegboard objects derived from Solid Works is for all exported STL to have a standardized centroid for placement in Gazebo world. Figure 4 shows how the object, in this case a cube, is centered about the xyz axes, with the minimum z is 0.0, which is also the centroid Z value.

Pics/pegboardcentroid.jpg

where

$$0 = x_{max} - x_{min}$$
$$0 = y_{max} - y_{min}$$
$$0 = z_{min}$$

Figure 4: Gazebo Centroid Location

For example, to satisfy the Figure 4 Gazebo centroid, the STL for the pegboards will need to be reoriented so that the xyz centroid now has xy centered around the origin, while the Z centroid is at the bottom of the array and sits flush on the robot table. Figure 5 shows the Gazebo xy centroid of the PEG ARRAYas compared to the Solid Works xy centroid.

In order to normalize the STL file to the Gazebo centroid, there are many software tools that are available for transforming the STL centroid into a Gazebo centroid [48, 49]. Over time many sophisticated CAD and Mesh Analysis tools have emerged, but a simple command line Python programming mechanism was preferred as it simplifies the learning experience. Further, the more complicated CAD tools used a proprietary Python backend to program the transformations.

The existing Python module “stl-mesh” was wrapped in a “TransformStlMesh”, which is a command line application that provides STL whole file transformations. TransformStlMesh uses “stl-mesh” to provide a set of common STL mesh transformation functions, including rotation, translation, scaling and axis centering of the STL. When the STL mesh transformations are completed, the code automatically generates a new file name with “_Centered” or “_ZeroZmin” or “_ZeroZmax” or “_Rotate” axes appended to original file name. For pegboard objects, TransformStlMesh was used to center xy and translate the mesh so that the minimum z is zero. TransformStlMesh also generates an STL mesh analysis report containing volume, Center of Gravity (COG), Inertial Frame, and min/max xyz.

Pics/pegboardholes.jpg

Figure 5: Pegboard Holes Centroid

Since the hole layout reasoning is tied to the CAD model layout and not to sensor reasoning, a hole's type and location must be defined. Hole locations on the pegboard are defined relative to the center hole. Fortuitously, the center hole has as its center the pegboard PEG ARRAY. The hole offsets are defined regardless of the orientation of the pegboard PEG ARRAY. Thus, to determine any given hole position, it is derived as an offset from the center of the pegboard and center hole location. Each hole and type is an offset from this centroid, as Gazebo model reports the centroid of features, so we must calculate the centroid of each hole subfeature based on its offset from the pegboard centroid.

Basic transform math can be use to generate a hole location (the Cartesian xyz of its pose) given the hole pegboard centroid consisting of its Cartesian location, and orientation given as a quaternion. Note, Gazebo uses the quaternion to represent rotation in a pose. Given the hole pegboard centroid as a pose, it is converted into a 4x4 Homogeneous Matrix representation, that is then multiplied by the i^{th} hole xyz offset to derive the hole Cartesian position.

$$
\begin{aligned}
P_{pegarray} &= gazebo\_getcurrent\_pose(pegarray) \\
T_W^{pb} &= Convert(Pose_{pegarray}) \\
Hole_i &= T_W^{pb} \times \begin{bmatrix} 1 & 0 & 0 & xoffset_i \\ 0 & 1 & 0 & yoffset_i \\ 0 & 0 & 1 & zoffset_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
where: & \\
P_{pegarray} & \; the\ centroid\ pose\ of\ the\ pegarray \\
gazebo\_getcurrent\_pose & \; Gazebo\ ROS\ model\ plugin\ to\ get\ current\ position\ and\ orientation\ of\ pegarray. \\
Convert() & \; function\ converting\ from\ Pose\ to\ Homogeneous\ Matrix \\
T_W^{pb} & \; defines\ a\ Transform\ from\ world\ to\ hole\ pegarray\ centroid \\
Hole_i & \; defines\ transform\ Cartesian\ position\ of\ hole_i
\end{aligned}
$$

Table 1 shows the pegboard PEG ARRAY of hole offsets. Hole 5 row is grayed and is equivalent to the centroid of the hole pegboard. Given the PEG ARRAY pegboard centroid, this table can then used to compute the centroid of any hole. The shaded row is hole 5, which has a (0,0,0) xyz offset from the centroid, so its xyz centroid matches the centroid of the PEG ARRAY. For the other 8 holes, each has xyz offset from the pegboard (0,0,0) centroid which is added to the actual hole pegboard centroid to determine the hole xyz centroid. All holes are even spaced in a 3x3 table with holes 1,4,5 on the highest z first step height, holes 2,5,8 on the second step z height, and holes 3, 6,9 on the lowest z third step height. Note, all offset values are in meters, the length units of Gazebo.

HOLE	X offset	Y offset	Z offset	X centroid	Y centroid	Z centroid
PEG ARRAY centroid				-0.09888	-0.5891	0.9351
1- round	0.0508	-0.0508	0.0143	-0.04808	-0.6399	0.9494
2- square	0.0508	0	0	-0.04808	-0.5891	0.9351
3- round	0.0508	0.0508	-0.0129	-0.04808	-0.5383	0.9222
4 - square	0	-0.0508	0.0143	-0.09888	-0.6399	0.9494
5 round	0	0	0	-0.09888	-0.5891	0.9351
6 - square	0.0508	0	-0.0129	-0.04808	-0.5383	0.9222
7- round	-0.0508	-0.0508	0.0143	-0.14968	-0.6399	0.9494
8- square	-0.0508	0	0	-0.14968	-0.5891	0.9351
9- round	-0.0508	0.0508	-0.0129	-0.14968	-0.5383	0.9222

Table 1: Pegboard Holes Offsets

Todo: Double check these are correct offsets - not really used in code. Currently, most simulated motion uses hard coded SDF world coordinate space that defines the pegs and peg boards locations NOT the Gazebo derived model information describing current model centroid and orientation.

As mentioned, the Solid Works STL export is normalized to Gazebo standard centroid format. This normalization process was done to all the pegboard objects so that any Solid Works STL object is first centered around the (0,0,0) and then translated so the the minimum Z is zero. Finally, all the pegboard objects were scaled by a factor of 0.002 so they are in Gazebo length units (meters) as well as a reasonable size for robot manipulation.

Listing 1 gives the SDF model listing for a ROUND PEG found in the Gazebo model database. The SDF tag <model> with name attribute "pegboard-roundpeg" contains XML elements that define the pegboard-roundpeg. The model is given as a collection of links, joints, collision objects, visuals, and plugins. (For brevity, the collision bounding box is omitted below.) We will go over some of the highlights of the SDF model definition.

Listing 1: Round Peg Gazebo Model SDF Listing

The pegs and all pegboard related CAD models were designed in Solid Works and exported as STL files. These STL file provide the visual element to a model and are located by using a Uniform Resource Identifier (i.e., <uri>) in the Gazebo model as shown in Listing 2. Each pegboard related object (i.e., PEG ARRAY, BASE ARRAY, round peg, and square peg) are defined in the Gazebo model database. These exported STL files serve as the image visualization for the <visual> element of Gazebo SDF.

Listing 2: STL Visual Mesh File Definition for ROUND PEG Gazebo

Gazebo uses a "world" SDF file to define the simulation and it contains a collection of robots and objects (such as tables, pegboards, and pegs), and global parameters including the sky, ambient light, and physics properties. For the pegboard world, we define five round pegs (i.e., pegs 1,3,5,7,9) in our Gazebo world, all using the same "pegboard-roundpeg" model but each having a different name and pose (position and orientation) to distinguish between the definitions. Listing 3 shows two of the five round peg definitions but each has a different pose (position and orientation).

Listing 3: STL Visual Mesh File Definition for ROUND PEG Gazebo

The <include> SDF element informs Gazebo what model to use from the database to define each fanuctask-feeder_peg#. The <pose> SDF element defines the pegs in world coordinate frame as a pose defined as (xyz, rpy) in the Gazebo simulation scene. Note, the difference in the ROUND PEG Cartesian z pose values, which is due to the tiered steps in the BASE ARRAY.

Scale is a ratio that represents the relationship between the dimensions of a model and the corresponding dimensions on the actual figure or object. In Gazebo, it helps in representing a model as either a larger or smaller model with comparative ease. Listing 4 contains a mesh STL ROUND PEG model definition, that is scaled by 0.002. The value 0.002 is first a conversion from millimeter STL units to Gazebo meter units (scaling by 0.001 factor) and then doubling the size of the converted STL model. Note, the holes in the pegboard hole array are a "fixed" diameter that depends on the scale of the pegboard, as it is difficult to individually scale subfeatures in STL. Likewise, all the pegboard objects have been scaled by the same value (i.e., 0.002).

Listing 4: Scaling Factor applied to ROUND PEG Gazebo SDF

There is a benefit to simulating the pegs as it is easy to alter the diameter of the peg by a scaling factor. Thus, during experimentation, pegs can be scaled to be smaller than the hole diameter, near exact fit to the hole diameter size, or larger than the hole diameter. The scaling factor should be uniform across objects, that is, either half as small, a quarter smaller, etc. in order to maintain a proper peg and hole fit. However, it is possible to marginally adjust the scale of the pegs to simply insertion of the peg into the hole or even make it impossible to fit.

Note, scaling of the pegs reduces or increases the diameter, but also scales the length of the peg, which effects total kinematic chain length involved in computing from the robot base, links, end-effector to the end of grasped peg object. Further, the location on the peg where the robot grasps the peg also changes the total length the robot kinematic chain. Because of the use of F/T sensing, once the peg is in the hole, the peg can be lowered until a F/T threshold is reached and the downward motion can be stopped.

Since the physics mass properties of the pegboard object can effect the simulation, the properties for mass and inertia are part of the SDF model definition. The inertia tensor encodes the mass distribution of a body, so it does depends not only on the mass, but also on how the mass is distributed through the object body. To get the ROUND PEG mass, a weight measurement scale was used. For the inertial vector, the TransformStlMesh provided an the inertial matrix as part of the log output as shown in Listing 5. From experience, it is important to give model and its links an inertia matrix that is at least close to the correct order of magnitude. Otherwise, the simulation will be flawed, with parts floating, flying, and other unrealistic behaviors.

Listing 5: Physical Properties of the ROUND PEG STL Mesh

```
```

7 Simulated Peg-In-Hole Case Study

Simulation can contribute to the cost-effective performance evaluation of robot assembly. But, there are aspects that limit the role that simulation plays today in intelligent robot design. For instance, simulation that is just a graphical visualization of the robot sequence of operations is insufficient for replicating real-world physics behavior. Instead, rigid-body physics-based simulation, where the physics of the robots, objects, and environment are modeled provides a higher fidelity approximation to the real-world. For example, the inserting of a peg into a hole in visual simulation could incorrectly overlay two images at the bottom of the slot (the PEG and PEG ARRAY) without consequence. However, in the case of physics based simulation, the PEG would “bounce” off the PEG ARRAY as it is physically impossible for a solid object to atomically combine with another solid object.

In our case study, we are more concerned with establishing a high-fidelity simulation of a robot peg-in-hole assembly using active F/T sensing for which various experiments can be performed. The NIST pegboard is well-suited for simulating the robot peg-in-hole operation, which is an essential task in assembly processes for manufacturing. Figure 6 shows the simulation setup using the NIST pegboard as both a container of pegs as well as pegboard of holes to insert the pegs. Note, the pegboard supplier and the pegboard destination are both single pegboards with no attached backboard PEG ARRAY. In the front, the pegboard contains pegs to insert, while the pegboard in the back of the figure contains empty peg holes that serve as a destination for the peg insertion.

In peg-in-hole simulation, a purely dead reckoning approach to inserting the peg in the hole is possible, since simulation does not inherently have errors. For example, in the real-world wear and thermal expansion errors could alter the precision of the robot as it attempts to insert the peg into the hole. Such errors could lead to an off-center theoretical-to-real hole target, resulting in a crash into the pegboard. For this reason, often simulations inject noise to make the simulations more “realistic”. Although dead reckoning appears to be an easy solution in simulation, one of the issues associated with making precise simulated robot moves is determining the exact length

Pics/PegboardScreenshot.png

Figure 6: Full and Empty Pegboard Setup

of all the links – especially the gripper. Any error in the kinematic modeling of the robot results in errors in robot positioning. For this reason, established robot kinematic models and visualisation were used and are a match for the actual robots, however, the simulated gripper was generated from a Schunk gripper model, which was not the actual gripper of the robot in the APRS laboratory. Hence, substitution and experimentation of different robots, end-effectors, or device configuration is easily possible using simulation.

Another distinguishing element in regards to a simulation peg-in-hole implementation concerns the various levels of robot command and control. At a high level, the command would be "peg-in-hole" and it is expected a lower level command structure would perform command and control of the assembly operation. At a high level, command and control has an expectation that the command will succeed and is actually more concerned with understanding error recovery. For example, what would a high-level robot command and control module do in the case of a dropped peg, or an impossible insertion scenario where there is misfit between peg and hole. Recovery from such errors is then a primary goal of higher-level reasoning. This level of reasoning is beyond the scope of this case study. At a lower level, there is an implicit F/T sensing performance requirement in a real-world robot assembly operation. One can expect force feedback to be approximately 1KHz bandwidth in order to be effective. Otherwise, trajectory motion must be slowed so that force feedback latencies do not result in undue delays which can result in the robot crashing because it cannot stop in a timely manner. Thus, you often see a tight coupling between the robot actuator control and the force sensor feedback in order to reduce latencies and achieve smooth, efficient motion control. Various performance metrics of a simulated F/T sensor, such as stiffness, compliance, or noise, are not dealt with in case study experiments. Further, we assume the F/T sensor is located in a traditional site, attached to the robot wrist. Du et al. provide a survey of strategies for implementing a wrist-based solution to dynamic assembly [50].

We will use a software architecture to describe the structural software components and relationships of the case study. For peg-in-hole assembly, the software architecture of the implemented system adapted for the simulation case study is shown in Figure 7.

./Pics/pegboardarchitecture.jpg

Figure 7: Pegboard Software Architecture

As background, the National Institute of Standards and Technology has conducted ongoing research on improving robot "agility" to adapt to changes in environment, tasks, and robots, and handle both spontaneous and unexpected task deviations. As part of the effort, the Agility Performance of Robotics System (APRS) laboratory has been constructed to further evaluate agility research under real hardware conditions. To further the dissemination of the agility research, NIST has produced a physics-based simulation of the in-house APRS agility lab incorporating ROS and Gazebo [2,51]. The peg-in-hole case study experiments are based on the APRS laboratory at NIST, which contains two industrial robots, a Fanuc LR-Mate 200iD and a Motoman SIA20F but replaced the kitting trays with pegboards. For the case study experiments, the Gazebo simulation world used a Fanuc robot with a parallel finger gripper, one pegboard to contain pegs to insert, and another pegboard with empty peg holes that serves as a destination for the peg insertion.

7.1 Gazebo

Gazebo is open source software, with simulated physics, robots and sensors, and near real-time performance running complex scenarios. These simulation features allow software development that performs nearly identically in simulation as on real hardware, thereby increasing productivity and code quality [52]. Gazebo has the flexibility to switch between physics engines, but we used the default including Bullet [53] Open Dynamics Engine

(ODE) [54]. ODE is an open source physics engines that supports simulation of rigid body dynamics using a C/C++ API. Gazebo simulates articulated rigid body structures, such as robots, which are created when rigid bodies of various shapes are connected together with joints of various kinds.

Gazebo uses an XML format called Simulation Description Format (SDF) to represent the world. SDF is used to define a simulation “world” containing robots, sensors, static and dynamic objects, lighting, terrain, physics. Moreover, plugins can be added to SDF for further refinement of robot simulation, control, and visualization. Since APRS is robot-centric the ability to model robots and their properties was a critical element. SDF contains robot descriptors for visualization, collision, physical properties, and robot control.

The pegboard simulation required simulating all the objects in the Gazebo world. This included the robots, gripper, pegs, and pegboards that are part of the peg-in-hole assembly application as well as the furniture, tables, and other objects in the APRS lab. We used the Gazebo preexisting library of models for tables, chairs, computers, monitors that were used. Also, a CAD model of the agility lab layout existed as part of the APRS simulation and was incorporated into the Gazebo world model. The next step was integrating the pegboard models into the Gazebo SDF World. Using the Solid Works pegboard CAD models, all the pegboard objects were exported as STL meshes and normalized to Gazebo units and centroid requirement.

The Fanuc robot was modeled using preexisting ROS URDF definitions [55]. Note, URDF is geared to describing robots, while SDF can describe a robot, the world, or any model in the world. However, the gazebo_ros_api was used to load the Fanuc robot URDF into Gazebo which required augmenting the URDF and XACRO files for the pegboard robots by adding some Gazebo URDF extensions (e.g., inertia, gazebo colors, etc.). Then the robots URDF models underwent were loaded by roslaunch using the gazebo_ros_api plugin.

The gripper was based on Schunk CAD models which were imported into Solid Works and then exported to URDF. The Solid Works to URDF exporter is a Solid Works add-in that will create a ROS package that contains a directory for meshes, textures and URDF files.

Plugins are a way to extend and add to Gazebo simulation functionality. With plugins, a programmer writes a modular piece of software with an a wealth of Gazebo and ROS API to access robotic and simulation functionality as opposed to digging into (or worse changing) the code base.A Gazebo plugin is a piece of C++ code that is compiled as a shared library and inserted into the simulation world SDF model. The plugin has direct access to all the functionality of Gazebo through the standard C++ classes. Gazebo plugins are useful for the following reasons: 1) allow access to any part of the Gazebo system, 2) are modular and self-contained, and 3) can be inserted and removed from a running system. Gazebo itself relies on software component technology, notably plugins, SDF to describe the world models, and existing gazeb_ros_api plugins to integrate ROS and Gazebo. All simulation extensions to Gazebo were done with plugins. The gripper grasping plugin was a customized plugin, while others (i.e., model plugin and joint update) were gazebo_ros_api off-the-shelf plugins.

7.2 ROS

The Robot Operating System (ROS) is an open source software framework that provides libraries and tools to help programmers create robot control systems and applications. The primary goal of ROS is to enable software developers to build robot applications quickly and easily on a common platform. The following elements of ROS were used within pegboard case study.

- **ROS core** is a collection of nodes and programs that are pre-requisites of a ROS-based system.The ROS core aggregate the packages required to use publish/subscribe, services, launch files, and other core ROS concepts.

- **ROS communication** is based on message passing between a set of ROS nodes. The communication messages are organized by topics which follow a publisher/subscriber pattern. Topics are either predefined or customized and includes messages for commonly used command and control, for example commanding or feedback of robot joints.

- **ROS services** are used to perform either asynchronous or syncrhonous request/reply communication with a remote procedure calls.

- **ROS param** is a parameter server that provides much of the configuration information for a ROS1 application. The ROS param is part of the ROS master that can be used for individual parameters (param), or in bulk through a YAML configuration file (rosparam).

- **tf library** was used for robot pose data modeling. ROS tf defines data types for: Quaternion, Vector, Point, Pose, Transform. Of note, CRCL data types were mapped into ROS tf data types.

- **Unified Robot Description Format (URDF)** was used to model robot link and joint relationships. Each robot in the APRS simulation provided its own URDF file. Existing ROS libraries (specifically URDFdom) can parse URDF and were used to standardize and simplify the extraction of kinematic parameters.

- **Semantic Robot Description Format (SRDF)** complement the URDF and specifies joint groups, default robot configurations, additional collision checking information, and additional transforms that may be needed to completely specify the robot's pose. As recommended, the case study generated SRDF using the MoveIt Setup Assistant [56].

- **Packages** are used to govern ROS development with code added to ROS by creating a new package. Packages can contain anything: libraries, nodes, message definitions, or tools. Above packages are the concept of a stack, which collects sets of packages that together provide useful functionality [57].

- **Gazebo/ROS Model Plugins** are part of the Gazebo_ros package, which has many ROS utilities and plugins that work with Gazebo. Often, Gazebo has a plugin that is encapsulated or improved by ROS. In addition, communication with gazebo_ros uses ROS topics, not Gazebo topics so it uses the ROS tool chain. Gazebo_ros was used to obtain the Gazebo object models current world pose. Thus, the centroid pose for peg, which is the (x,y,min z) Cartesian location and orientation, is attained using this plugin.

- **MoveIt!** is a set of software packages integrated with the Robot Operating System (ROS) that has numerous capabilities, mostly geared for autonomous navigation, but does provide the ability to execute robot Cartesian motion plans. Since Moveit! is a bit overkill for kinematic and Cartesian motion planning, we integrated Open Robot Control Software (OROCOS) [58] Kinematics and Dynamics Library (KDL) to provide forward and reverse kinematics, as well as trajectory and joint motion planning. Fortunately, KDL is integrated into ROS and supplies a URDF parser that we used to build the KDL robot kinematic chains. We used the KDL motion planning as at this point, we did not expect any obstacles, so were not concerned with collisions and obstacle avoidance, which is a strength of Moveit! trajectory level motion planning.

7.3 Grasping

The peg-in-hole assembly robot application relies on grippers and grasping for the manipulation of pegs. Because of its practical importance, grasp planning has been extensively investigated. The reader is referred to [59–61] for a general introduction on grasping. Recent grasping work can be found in [62]. We relied on typical grasping that required the use of open/close two finger grippers. The grasping operation itself is a simple scenario, the robot centers the gripper around the peg and then closes to grasp the peg. The emphasis of the physics based grasping simulation is close/carry/open two-finger gripper control. As simple as this scenario appears, there is real-time simulation factor, friction, collision computational loading that effects the gripper responsiveness, which is mathematically intense due to complexity in collision handling.

In the real-world APRS lab, the robots perform grasping using pneumatic parallel grippers. A typical ROS approach for defining parallel grippers in software involves mimic joints, where one joint "mimics" a second joint by maintaining its relative position and velocity in joint-space. Mimic joints are passive joints that linearly mimic the motion of independent active joint in a kinematic loop. Use of mimic joints are a common method to synchronize the symmetric closure of a parallel gripper. However, physics-based simulation of gripper actuation lack "mimic" joints, so operation the resulting finger positions would not be symmetric. Because of this, a popular ad-hoc approach is to use external control plugins [63] which implement a proportional-integral-derivative (PID) force controller that uses the mimic joint's relative joint position as the feedback term. However, there are problems with using such a control scheme for parallel grasping such as the lack of a guarantee that the gripper's fingers will remain symmetric throughout a trajectory especially if they experience different external forces. To remedy many of these shortcomings, we used the Gazebo APRS grasping plugin developed at NIST by Piliptchak [1].

The APRS grasping plugin was designed to handle many small objects. This introduces two challenges to physics-based simulation. The first challenge is simulation stability. The stacking of objects, especially objects with large inertia-ratios, is known to cause instability due to over-constraining the linear complementarity problems (LCPs) that are solved by the physics engine at each time step [64]. The second challenge is compute speed, which deteriorates as the number of contacts to simulate increases. To improve both stability and computational performance, the Gazebo APRS grasping plugin automatically simplifies contacts between relatively stationary objects. The Gazebo APRS grasping plugin offers an improvement over previous dynamics-disabling features found in Gazebo's primary physics engine, which only applied to absolutely stationary objects [64]. It is also fairly physics engine-agnostic and lightweight, provided the physics engine supports measuring constraint forces and dynamically spawning joints.

Overall, rigid-body physics engines are adept at tackling specific simulation problem areas, such as numerically stable contacts and joint articulations [65–67]. However, a significant amount of effort needs to be put into defining contact behavior, inertia matrices, friction coefficients, and numerical solver parameters to ensure acceptable performance [64]. This effort becomes increasingly laborious as the simulated environment becomes more complex.

The Gazebo APRS grasping plugin is loaded into the Fanuc world as a Gazebo plugin and listens for ROS Service command requests. The APRS grasping plugin uses a ROS workspace to define both the ROS Service topic and the Gazebo plugin code both required to encapsulate an open/close Service command. The APRS grasping plugin Service invocation can be synchronous (i.e., returns when grasp has completed) or asynchronous (i.e., returns when Service command received), but asynchronous has proven to provide more robust behavior.

7.4 CRPI

The Collaborative Robot Programming Interface (CRPI) software is intended to provide an architecture to support the metrology of collaborative robot performance by means of commanding a myriad of robot platforms simultaneously with a singular command structure [68]. CRPI was developed to be an instantiation of the conceptualized model of the Canonical Robot Command Language (CRCL) messaging language to communicate with the robots [69, 70]. CRPI itself is an API client-server architecture. CRPI is the client API interface with numerous objects and function calls that connects to a robot which acts as a server then fulfills. CRPI has many extensions beyond CRCL based on satisfying real-world application requirements. As such, CRPI contains additional software functionality to address peg-in-hole programming requirements. Specifically, CRPI includes peg-in-hole micromotions that were developed to do "real-world" peg-in-hole assembly demonstrations in 2015.

CRPI is intended to provide a composable robot system by using a uniform robot Application Programming Interface (API) type definitions and declarations that serves as the front-end to command a myriad of back-end robot platforms. CRPI uses a C++ or Python API as a programming front-end with the back-end expressly coded using the proprietary robot socket or serial communication stream. CRPI uses the trajectory and joint planning of the underlying robot for motion control. Since we were using a Gazebo robot simulation which does not provide these services, we used linear and spherical interpolation between goal and way points as this was sufficient for simulation and the most expedient.

Of most interest from CRPI was its peg-in-hole micromotion hole searching strategies. Hole search is generally done by locating the hole center using a vision-sensor or by using blind search techniques. For our F/T case study experiments, we assume a blind search. CRPI defines a collection of implemented blind hole search assembly primitives, including:

- **Random** uses a random walk to determine hole location. The random search is defined by the radius of the search region and includes a flag for determining whether to allow the search to explore beyond the radius.

- **Spiral** uses a spiral motion from the center where contact was detected expanding outward until either the hole is detected or the location of the search area limit has been reached. The spiral search is defined by clearance between peg and hole in mm, the distance between turnings. and the radius of the search region. Lans et al. have an in depth discussion on spiral motion [71].

- **Square Spiral** uses a rectangular spiral motion from the center where contact was detected expanding outward until either the hole is detected or the location of the search area limit has been reached. The square spiral search is defined by the search step size and the search radius.

- **Raster** uses a rectangular side-to-side pattern from top-bottom or left to right starting at the outward boundary where contact was detected tracing side-to-side in a rectangular pattern until either the hole is detected or the location of the search area limit has been reached. The raster search is defined by the number of rasters to create in the search area, the width of the search area and the length of the search area.

- **Hop** adds a hopping element to the search with a magnitude defining maximum displacement from the current position and the frequency the rate at which the tool tip center is moved up and down.

- **Rotation** uses a rotational search (rotating the part back and forth along the Z axis) given the range is defined as the maximum rotational offset and the speed defines the speed at which the part is rotated.

- **Circle** uses a circular search (moving the tool center point in a circle) to the queue, given a radius of the circle pattern.

- **Linear** uses a linear search to the queue, whereby at boundary condition the robot hops to the adjoining search location. The linear search is defined by an x offset for the X axis distance offset, a y offset for the Y axis distance offset, and a z offset for the Z axis distance offset.

- **Constant offset** adds a constant distance terminator condition as defined by an x offset for the X axis distance threshold, a y offset for the Y axis distance threshold, and a z offset for the Z axis distance threshold.

These search strategies employ a variety of micromotions that should only require a centimeter^2 maximum in search area and that is also achievable in a relatively short time frame. Otherwise, the use of a camera to narrow the searching area would be necessary to make the implementation practical. In general, search strategies are evaluated in terms of execution time, precision, stability, and applicable geometries and features of parts. Jiang et al. provide a classification of state of the art in search strategies [72].

For case study experiments, since CRPI is primarily a Microsoft Visual C++ Studio front-end, it did not seamlessly build with Microsoft ROS Noetic Visual C++ 2019. Instead, peg-in-hole related portions of CRPI were ported to build with Microsoft C++ 2019 and ROS catkin_make.

8 Peg-In-Hole Experiments

A great deal of research of the robotic peg-in hole assembly operation has evolved over the past decades. In the real-world, peg-in-hole assembly makes the assumption that the system is heavily influenced by uncertainties coming from mechanical, sensor, and control errors. In order for a simulated peg-in-hole to be valuable, it must understand and replicate these real-world uncertainties. At worst, a simulation may not understand how or why errors occur, but should be able to offer a reasonable approximation to the error and cause the errant behavior. Further, there is a wealth of research concentrated on real-world peg-in-hole error detection and error recovery strategies offering a multiplicity of different issues and solutions. The simulated peg-in-hole task description and accompanying experiments are presented with an emphasis to validate what is achievable, reliable, and consistent in reproducing real-world challenges. We start with a general peg-in-hole model and offer some experiments that explore the simulated model. These experiments are by no means mathematically rigorous or scientifically complete, but establish that F/T sensing of peg-in-hole is possible in Gazebo and provide a glimpse into the possibilities of using a simulation rigid-body physics engine equipped with a F/T sensor.

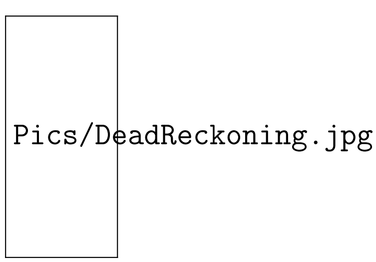
Foremost, we will attempt to classify the multitude of peg-in-hole algorithms. The majority of research is either in support of a new passive insertion technique, or new sensor enabled active compliance technique. Most if not all solutions are in support of a overcoming an imperfect world, where the peg undergoes some real-world challenge before mating with the hole. The initial focus of peg-in-hole analysis of algorithms will be on understanding the issues that arise while inserting the peg, and then classify the responses based on the error. Often there is no "correct" solution and instead a solution based on the application or circumstance is preferred.

Of note, potential solutions are more broadly applicable than one might find in our domain of interest, manufacturing. For example, let us assume we have an android personal assistant robot with a key in hand ready to open a door in the dark, and then have to use a tactile based search for the keyhole with the key in order to insert the key, unlock the door, to then open the door. Such confluence of challenging occurrences would not typically be found in a structured manufacturing environment, but at a micro-level of operation may be necessary to smartly "wiggle" a key into a hole. It is the subtle adaptive behavior that humans routinely exhibit, but robots struggle with.

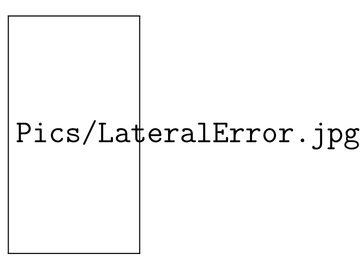
Our case study uses a Gazebo simulated Fanuc robot to act as a test platform to explore many elements such as F/T feasibility, hole searching algorithms, contact forces, and peg insertion strategies. The research is by no means complete but establishes that open-source physics-based F/T simulation is possible and that many opportunities await.

8.1 Peg-In-Hole Task Description

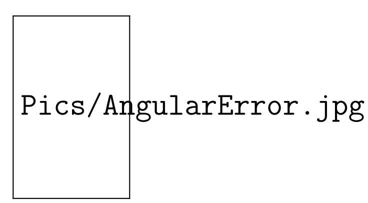
The peg-in-hole case study task description is summarized as follows. A disassembled pegboard starts with a series of nine peg holes (both round and square), and an assembled pegboard of identical layout but containing pegs. Initially, the allotted pegs were limited to round pegs, which provided better spacing between pegs to insure easier clearance for the robotic gripper to grasp pegs. Thus, we assume all pegs are vertically held by a pegboard with easy grasping access for our gripper. There are a cacophony of issues related to developing a peg-in-hole insertion model of operation. One area not covered concerns aligning the pegs shape to match the hole shape when presented in different orientations. We assume part mating is geometrically matched. The two major issues we will address in peg-in-hole assembly are one's arising from a small error in lateral or angular misalignment that require remedial action to enable the insertion. Figure 8b shows an error in the peg location relative to hole, while figure 8c shows the misorientation of the peg relative to the hole. Otherwise jamming could occur and cause damage to the assembly robot and or the mating parts.



(a) Dead Reckoning Insertion



(b) Lateral Misalignment Error



(c) Angular Misalignment Error

Figure 8: Alignment of peg and hole during an assembly operation

Figure 8a shows a part mating with no or little misalignment. Dead reckoning can offer possible strategies for dealing with minor misalignments. Analogous to a human wiggling a peg into a hole, a robot could impart minor random "wiggling" in a lateral back-forth direction, which simultaneously imparting a small downward force until the robot detects that the peg is positioned in the hole. There is a fine line between wiggling and "jamming" the peg into the hole that could cause damage to the robot and or the mating parts. Chamfered holes and/or pegs provide further compensation to the dead reckoning to make part mating even more likely. Du et al. [73] found it is often desirable to introduce small-amplitude random vibration or dithering during parts mating to overcome stiction. Dead reckoning compensated insertion should be expeditious and predictable or a timeout would be necessary. NIST CRPI framwork has search functions that are also applicable to effect various dither/wiggling micromotions [74].

Figure 8b shows a part mating lateral error, we assume the peg will be approach the hole but instead of "perfect" insertion path, the robot F/T sensor will detect contact between the peg and the surface. So, when the robot has achieved an approximate location of the hole and at the same time detects an increase in the F/T due to contact, we can assume that a lateral misalignment has occurred and we must now "search" for the hole. For our case study experiments, we apply the CRPI search algorithms to find the hole center to enable insertion.

Figure 8c shows an angular peg error, where the tolerance between the peg and the hole plays a significant part in assessing a remedial action. Depending on the circumstances, we may find a peg off-center in the hole that needs to centered, a peg that is skewed in orientation compared to the hole that must be aligned to the insertion vector of the hole, a relaxed grip to allow the peg to wobble "back/forth" into the hole, a micro-spiral in order to find a lower contact F/T relationship between the peg and the hole, among other potential remedial actions.

8.2 Study of F/T Sensor during contact in attempting Peg-In-Hole

This section discusses some active compliance tests using the Gazebo F/T plugin situated at the wrist of the Fanuc LR Mate. We run some tests to validate the functionality of the F/T plugin, as well as uncover some weaknesses in our software base.

Figure 9a shows a graph of F/T Z-axis values as the robot approaches the hole in a completely vertical descent in the Z axis. The Z F/T values are essentially zero, until the peg makes contact with the hole array surface. The experiment runs the robot into the hole array surface (purposely missing the hole) until the F/T Newton force Z value > 0.05N and then stops. If you examine the visualization of the robot Z axis descent, you can notice a push-back by the hole array surface to the peg, indicating that the stopping contact force is too large.

As for the repeatability, the F/T Z values were close enough, but there is currently much latency between approaching position to the hole array surface, due to poor responsiveness of Gazebo to service command. A lower level Gazebo guarded move plugin with much higher responsiveness was coded but not successful deployed after many attempts. The Gazebo guarded move plugin was coded to command the robot to initiate motion in a certain direction while monitoring F/T value that would trigger a stop motion, when, for example, a Z F/T value exceeded a force threshold,

One of the more interesting research aspects that must be considered when using robot assembly simulation is the variability of the physics engine to perform as expected. When combined with programmer error, this can lead to flawed expectations. For example, a peg should drop to the bottom of its hole but given friction, stiction, or

Pics/FTDetectionOfCollisionSurface.pdf

(a) F/T Values During Collision With Hole Peg Array Surface

Pics/RobotFTzSurfaceContactContact.jpg

(b) Gazebo Visual Snapshot of F/T Contact

Figure 9: Gazebo F/T Plugin Z Response

worse possibly a software glitch the peg may not rest in the final centroid position. Having observed this behavior one can anticipate some problems. Thus, observing and persevering through these idiosyncrasies merits a warning that rigid-body physics engines are a rather new and enabling force for simulating complex physical realities but are not foolproof. As these rigid-body physics engines mature (as well as inherent computational power), many of these problems will disappear.

The initial replication of the force based contact experiment did not yield the results one would expect, and in fact, they differed due to a variety of issues. One issue was the difference in expected top-of-peg height that was different between runs - the initial SDF world model and a later reinserting the peg into its original pegboard hole. However, using an initial run of the contact-peg-forces experiment did result in highly replicated results with minor differences in F/T simulated sensor readings.

Todo: Develop experiment resulting in a graph of F/T values when the robot approaches the hole or surface with a 20^o offset angle during a vertical descent in the Z axis.

8.3 Peg-In-Hole Dead Reckoning Algorithm

The dead reckoning Peg-In-Hole algorithm, which assumes ultra-precise robot motion, and no imperfections in the pegboards, follows. First, the robot must select a peg from the supply pegboard. Next, the robot grasps the selected peg in a hole slot. Then, the robot vertically retracts upward away from the supply pegboard slot. Once retracted, the robot traverses to a position directly overhead of the matching assembly pegboard hole type. Once situated above the hole, the robot vertically lowers the peg into the hole, releases its grasp of the peg, and then retracts from the peg. The robot speed of simulated dead-reckoning peg-in-hole is unimportant, except for the closing grasp operation on the peg, which has some contact latencies that need to trigger before there is an actual “virtual grasp”.

There can be difficulty when using dead reckoning insertion for insertion objects and hole shapes that are misoriented, for example, a rectangle that is aligned lengthwise instead of width-wise. For this misoriented situation, the insertion object centroid and the hole centroid must be in alignment, and then the insertion object must reoriented to match the hole shape without any lateral Cartesian movement of the insertion object. Using a robot to reorient its end-effector is commonplace for robots with an articulated wrist. An additional challenge is possible if the hole is askew and not aligned along a primary axis. Li et al. [75] discuss use of robotic assembly for irregular shaped Peg-in-Hole. Given the relative ease to modify the pegboard CAD design, it is possible to increase the complexity of the shape and forms of the pegs and holes.

In spite of the ease of peg insertion, the dead-reckoning approach offers opportunities for exploring F/T response in various circumstances. One experiment is to alter the orientation of the peg once inserted in the hole to understand the F/T reading simulated sensor reading under a known state. Another experiment is to alter the orientation while retracting and grasping the peg to understand the forces in reverse.

Pics/PegAssumbly.mp4

Figure 10: Dead Reckoning Peg Assembly Movie - click and accept

Figure 11a shows the setup after a peg has been inserted into a hole using dead reckoning. Figure 11b shows the final test peg orientation in the hole after 10 negative degree increments. The orientation starts with a 90^o pitch orientation in the hole and Figure 11b givens the final pitch orientation as 80^o . If one looks closely at the hole in Figure 11c, there is a gap between hole boundary and the peg, which could be related to the increased size of the hole to the peg based on the tolerance, or some other possible simulation issue.

Pics/PegInsertedIntoHoleDeadReckoning.jpg

(a) Dead Reckoning Peg in Hole

Pics/PegAfterTwistWhileInHoleDeadReckoning.jpg

(b) Twisted Orientation of Peg in Hole

Pics/HoleGapPegAfterTwistWhileInH

(c) Twisted Peg in Hole Gap

Figure 11: Twisting Peg in Hole Observations

Figure 12 shows the F/T readins during the experiment to test tilting the peg pitch orientation while already in the hole. As expected the XYZ forces increase, with the Z F/T value exhibiting the largest increase in a negative direction.

The Z force indicates a negative force as the pitch twist angle deviates from perpendicular, so it acts in a negative direction based on the coordinate system.

Pics/twistplot.jpg

Figure 12: Tilted Peg Forces

8.4 Wiggling Peg-In-Hole Insertion Algorithms

The goal of this experiment is to perform a simulated wiggling of a peg into a hole. This wiggling procedure is important for peg and hole tolerance that are nearly identical, and the peg could become “stuck” while inserting the peg. In order to test a wiggle using the existing NIST pegboard dimensions, one would be required to enlarge a peg to almost an identical size as the hole. This can be achieved in Gazebo by increasing the peg STL scale multiplier until just fits in the hole.

Algorithm 1 describes the steps in wiggling a tightly tolerance peg into a hole. Lans and Lillqvist use a modern compliant commercial robot to describe an algorithmic approach to wiggling a peg into a hole [71]. As mentioned, often the tolerance between the peg and the hole can be very tight leading to jamming. Using a constant downward force while attempting random tilting micro-motions with the peg could overcome jamming. Minor reorienting of the tool tip to prevent jamming and to effect wiggling is not done in the same way as moving the tool tip in a predefined trajectory. The x, y and z-coordinates needs to be static while the orientation has to be manipulated based on the forces recorded on the peg.

Todo: Develop accurate model of peg array with hole offsets to determine top of hole, implement algorithm in code and record simulation video.

Looser tolerances between the peg and the hole can have a more In this case, the wiggling consists of deliberately changing the direction of peg insertion by rotating a peg about both the insertion axis and its tip. The algorithm describing it may be outlined as follows:

- tilt peg with respect to the surface of the hole,

Algorithm 1 Wiggle Peg into Hole Algorithm

Require: $maxZforce, maxXYOrientationOffset$

assume missing hole target slightly < 0.002 m

assume slight misorientation

while $F_z > maxZforce$ **do**

downward force in Z direction

random wiggle in xy orientation direction

monitor forces to detect decreasing force

end while

- repeat
- push peg inside hole,
- rotate peg anti-clockwise slightly about the hole axis

So far only the algorithmic approaches have been developed that would be used in simulating a "jammed" peg being inserted into a hole - either a very tight tolerance or a looser tolerance. In the real world, one could record teach robot positions for grasping the peg, the location of the top of the hole and then program a wiggle. To simulate properly, one must model the kinematic chain to the top of the hole in a pegarray. For these tests we want the top of the hole in which to place the peg, which requires a more complete model of the pegboard and especially the peg array. In defining the pegboard model containing the pegs the Gazebo SDF has been defined using world coordinates (in the Gazebo world).

Listing 6: Gazebo Reporting of Current Peg Model Names and Locations

```
```

Todo: To Be done: Implement accurate model of peg array with hole offsets to determine top of hole in code, use micromotions to search for hole, and record simulation video.

8.5 Study of Hole Searching F/T

A most critical technical bottleneck to robot assembly is to find the best search strategy to improve positioning accuracy in assembling. Jiang et al. [72] present a review of the state of the art of search strategies and identify ways to improve existing algorithms.

In general, search strategies are evaluated in terms of executing time, precision, stability, and applicable geometries and features of parts.

One of the issues involved in developing a peg-in-hole algorithm,

In the force sensor based peg in hole assembly search strategy, the search path is pre-set in the search algorithm, and a threshold value is set for the force/torque (F/T) generated during the peg and hole contact, and the feedback control of the F/T sensor is used to achieve the peg-in-hole assembly search task when the assembly robot is unable to meet the accuracy of autonomous assembly due to large errors during positioning and repetition.

Ongoing research at NIST has developed and applied the Collaborative Robot Programming Interface (CRPI) software library to various robot and gripper ability, dexterity and collaborative tasks. CRPI areas related to our research included robot peg-in-hole as well as robot assembly. CRPI explored numerous search and insertion strategies that will serve as a starting point in understanding our peg-in-hole research.

1. First, the robot grasps the peg and positions the end effector in either an upright or at an angle.

2. Next, while the robot is grasping the peg it moves toward the hole, until contact is detected which corresponds to an increase in the F/T sensing. The rate of the robot approach to the hole/surface depends on the latency of the F/T feedback reporting. Smaller latencies mean faster detection of surface and faster stopping of searching motion. Even with small latencies, the robot motion cannot be excessively fast, of it will still crash into the surface.

3. Upon detected contact with the surface, the robot now starts to search for the hole maintaining contact with the surface and using a micromotion planner to move the robot grasped peg. Upon a change in the detected F/T feedback it is assumed the peg is now in contact with the hole and switches to an insertion strategy.

We have two basic hole searching algorithms: spiral and raster. The spiral algorithm is a common approach to hole finding that uses an increasing circular path upon each rotation around its initial surface contact point. Park et al. [76] discuss a compliant peg-in-hole assembly method based on blind searching using a spiral force trajectory.

The raster algorithm is another common approach to hole finding. The raster micromotion planner sweeps back and forth across the surface until it detects a change in F/T indicating lower contact because of the hole. The raster uses the contact point as the center of the raster and then uses a fixed width and height to start an expanding rectangle raster search. A different approach could use a "top" to "bottom" search covering one row at a time.

Todo: To Be done: Develop algorithm, code and record simulation video

Summary Peg-In-Hole F/T Insertion Algorithms

Search is generally done by locating the hole center using a vision-sensor or by using blind search techniques.

1. Grasping: First, a peg in the pegboard is is grasped with the two finger finger as indicated. One could argue that the experiment would be more robust if the peg was in various orientations, either upright, sideways, etc. However, we assume a peg standing upright in the pegboard with a centroid returned by the Gazebo simulation/ From the centroid and the length of the peg, we can determine the location on the peg where to grasp the peg. The Gazebo grasp plugin uses a physics-based approach mechanism based on closing forces which center the gripper around the peg shaft as it closes.

2. Approach: Depending on the insertion strategy, either the peg is grasped upright or the peg is grasped slightly tilted, approximately 20 degrees from vertical.

   For a slightly tilted peg it allows for a peg-in-hole insertion with sufficient angle for first detecting one side hole force contact and then a two sides in the hole force contact.

3. Approach: In the approaching phase, the angle distance relation shows that users tilts the peg in its approach in a rather systematic way.

4. Insertion: The insertion phase is guided by the occurrence of a sideways force that aids the human in maintaining a correct position of the peg relative to the hole. This particular force-event is recognizable

prior to the angle-alignment between the peg and hole, in particular for the peg with a tight fit due to the increased necessity for a proper alignment.

Peg-In-Hole assembly has been the benchmark force-controlled robotic assembly. It involves two main stages. The first one aims at placing the peg center within the clearance region of the hole center, known as the search phase. The next step is to correct the orientational misalignment, known as the insertion phase. The insertion has been widely researched as compared to the search phase. Search is generally done by locating the hole center using a vision-sensor or by using blind search techniques [28].

Pics/AimofSearchstageistolocalizePegCenterwithinAssemblyClearance.jpg

Figure 13: Aim of Insertion Alignment Phase

Much of the research literature studies the peg-in-hole insertion assuming a peg tilt and then a centering "wobble"[2] while descending into the hole. We wish to observe the forces seen when contacting one hole side, and then both hole sides. In either case, an upright in-place gripper orientation should find the peg in the hole center. Experiments were run to test the hypothesis.

In the robot all-zero joint position, the Fanuc LR Mate robot is in the home position as shown in Figure xxx. This produces a home Cartesian pose yyy. In order to achieve a downward pointing gripper to allow the peg to be picked up, we rotate the along the Y axis (pitch) for 90 degrees, (i.e., [0.000000,90.000000,0.000000]). This gives us a resulting quaternion of (0 0.707107 0 0.707107).

Many of the research teams use a tilted peg, so we also studied the measured simulated forces when a 20^o angle approach to hole was used.

One method to tilt the peg is to rotate along the Y axis (pitch) an additional 20 degrees, (i.e., [0.000000,110.000000,0.00 giving us a resulting quaternion of (0.000000,0.819152,0.000000,0.573576). Another method to tilt the peg is to rotate along the X axis (roll) -20^o, while maintaining a 90^o (i.e., [-20., 90.0, 0]) giving us a resulting quaternion of (-0.122788,0.696364,0.122788,0.696364).

[2] others

8.6 Challenges using Gazebo and Simulation when Implementing Peg-In-Hole Algorithm

Currently the major impediment to accurate simulation is the lack of accurate complete models and accompanying routines. For example, even though Gazebo can supply a bounding box of the peg, giving a the top location of the model, the routine has not be integrated into peg-in-hole code base. Further, subfeatures, such as holes require the feature offsets from the centroid to be explicitly modeled, and unfortunately, the STL dimensions are unit-less on purpose.

inevitably requirement to implement and understand all workspace objects. For example, using SDF can give you the

where you grasp an object

partial models - for example, what is the difference between the lower centroid Z and the upper Z in the hole peg array. STL only reports a unitless numeric range that did not directly map into a concrete number. For example, the Z height of the hole peg array was 88.5 but no units.

9 DISCUSSION

Simulations are invaluable tools in developing industrial robotic systems. In situations where hardware resources are limited or too costly to use, simulations can provide a test-bench for developing controllers, debugging software, and testing various work-space configurations [**?**].

Robotic peg-in-hole assembly is a very complex dynamic process. A complete analysis of the geometric and dynamic equilibrium conditions has established a general assembly model for a certain goal: to understand the mechanism of dynamic insertion and the development of compliant devices capable of avoiding wedging and jamming in high speed assembly operation [33]. One of the limiting factors to using a simulation in place of a real system is how well it replicates the physical dynamics of the real system. This discrepancy has inspired the development of new rigid-body physics engines that tackle specific problem areas, such as numerically stable contacts and joint articulations [65–67].

We study a peg-in-hole simulation that uses the NIST pegboard and pegs (round and square pegs) as well as a platform base array and hole array of even-spaced holes in which to insert the pegs. Peg-in-hole is one of the most common in manufacturing assembly industry [25]. Peg-in-hole, which is extremely trivial for any human, is surprisingly challenging for a robot.

The Gazebo simulation uses the existing Agility Performance of Robotics System (APRS) laboratory robots simulation setup and place several pegboards instead of kits. One pegboard contains pegs to insert, the other pegboard contains empty peg holes that serve as a destination for the peg insertion.

Unfortunately, in the real world it is often easy to get acceptable behavior from a system. In simulation, it may not be that easy to configure physical properties to replicate the real behavior and thus accurately simulate. As was found, understanding and modeling the physical properties in real-time using a physics modeler can be challenging. For example, in order to properly use the physics functionality, the weight, size and inertia of kitting objects must be specified. Friction, collisions, and integrators are especially troubling when combined with excessive loading on the real-time simulation factor (often under 50%). We used Gazebo with ODE, which only seemed to work with hard contacts in its physics evaluation. The use of hard contacts means that ODE uses a special non-penetration constraint is used whenever two bodies collide. Although computationally more efficient, simulated object behavior often incurs disastrous failures. In particular, the following issues were noted:

- gravity and forces apply and computing gravity initiated contact can be computationally burdensome
- entities cannot go through solid objects
- entities can be moved, rotated, removed or added, just like real-world objects, but must be modeled correctly with regard to weight, size, COG, inertia.
- entities collide with each other when in contact, enabling the simulation of complex object interaction, that is quite difficult to comprehend.

In spite of the issues with physics and sensor based simulations, under stable conditions simulation can be particularly realistic for moving objects in a virtual world. Gazebo integrates standard robot representation and visualization mechanisms in a straightforward manner and has the capability to calculate physical properties for robots. However, only a thorough understanding and model of the required physics will result in an accurate simulation of a real environment with all of its objects and related physical properties included.

Often, only a thorough understanding and a complete model will yield an accurate simulation of a real environment. Depending on the real world requirements, this may lead to a large undertaking requiring detailed representation of simulated objects with a finer level of detail not easily attainable through the simulation model (e.g., object subfeatures) which can require time consuming effort. In fact, although Gazebo simulation of the pegboard using a dead reckoning approach and hard coded peg and hole locations worked with relatively ease, adjusting the modeling approach to a offset-driven, dynamic model of the objects was time consuming and fraught with troubles.

In future research, numerous aspects of the peg-in-hole experiments that could be improved or better programmed will be developed.

- robot approach motion to a hole (or surface for contact test) before contact is initiated is very slow and cautious. This is in order to be able to stop robot motion upon detection of contact with the force sensor, and to avoid crashing into the surface. It must be noted that using the Gazebo simulation we can stop the robot immediately if we detect contact, as there is no simulated physics involved in stopping motion. However, should we cause collisions between objects, this can lead to the robot dismantling or other quirky happenstance.
- faster Gazebo simulation than synchronous command and sensing. The use of synchronous operation simplifies concurrency pitfalls, such as racing, where the latest value is an older value. Having all facets of the control and simulation in lock step may simplify (or not) the concurrency quandary.
- better integration of ROS moveit! and the Gazebo simulation. Currently, the Gazebo model is a stand alone synchronous service that does not use ROS asynchronous topic communication, in order to reduce the concurrency issues discussed previously.

- there a numerous improvements that could make for a better software development environment. Although ROS on Windows used community Visual C++ 2019, compilation can take a while, especially if one is not using pre-compiled C++ headers which speed up compilation immensely. Although an implicit assistance in Visual C++ IDE, using the pre-compiled headers is First, as shown in the listing 7 the following snippet was added to enable all cpp files in the target to use precompiled headers if available. The name of the precompiled header is stdafx.h (as commonly used in Visual C++ software projects).

Listing 7: Using Precopmiled Headers in CMake for Visual C++

Then, stdafx.h contains the collation of include files found in the project.

- another discouraging software development issue relates to the excessive amount of time it often takes to fully load Gazebo and all aspects of the its simulation – server, client, models, plugins, etc. And note, without the Windows subsystem for Linux (WSL) installed, Gazebo operation does not work, but does not display an error, just return done. The delay in loading is due to the fact that Gazebo is implemented in the WSL OS layer and then displays using an X Window win32 application. Listing 8 shows some of the assortment of include files used by the test_gazebo_package package.

Listing 8: The Contents of the stdafx.h Precopmiled Header used by CMake for compilation of all the C++ source files.

Demonstration code for this report can be found in the NIST github public repository found at https://github.com/usnist
Details on using the code base can be found in Appendix! A.

Appendices

A Peg-in-hole Repository Details

Software was developed for peg-in-hole experiments that consisted of two ROS workspaces:

1. Gazebo pegboard world called gzpegboard,

2. F/T experiment repository called crpi_test.

Note for Windows developers, there is a very important caveat in order for Gazebo to work on a Windows distribution - the Windows Subsystem for Linux (WSL) specifically **WSL 1 must be installed for Gazebo to work**. Note, we found WSL 1 sufficient, while WSL 2 was inoperable. ROS noetic does not need WSL, however, when we uninstalled WSL we found that Gazebo no longer worked. There is no mention of this in the Microsoft distribution of ROS 1 noetic. One final caveat regarding the Microsoft ROS noetic distribution, Gazebo material, specifically textures, did not seem to work.

The first ROS workspace handled the Gazebo simulation of the pegboard world. Figure 14 shows the Gazebo visualization of the pegboard world. This includes launching a Gazebo client and a Gazebo server. The Gazebo server (gzserver) reads the pegboard SDF World file to generate and populate a world. The Gazebo client (gzclient) connects to a running gzserver and visualizes the pegboard world. The gzclient is also a tool which allows you to modify the running simulation.

./Pics/GazeboPegboardWorld.jpg

Figure 14: Gazebo pegboard world

A.1 Gazebo pegboard world Workspace

The Gazebo simulation of the pegboard world ROS workspace contains a Windows batch file that uses roslaunch of the Gazebo pegboard world. The roslaunch tool is the ROS mechanism for launching multiple ROS nodes, as well as setting parameters. To simplify distribution, we localized all the Gazebo pegboard SDF world definitions in the gzdatabase folder contained in the workspace, The gzdatabase folder is similar to the Gazebo database in that it contains both models and material SDF definitions.

First we examine the Windows batch file that sets up the Gazebo environment variables, and start the simulation. Listing 9 shows the change to the bin folder under the gzpegboard workspace and starting the“gzpegboard” batch command file. Note, there is no catkin required to start the Gazebo pegboard world simulation, as all the ROS components already exist in the noetic ROS distribution (roscore, Gazebo client/server).

Listing 9: Use batch file to start the Gazebo pegboard world

The Gazebo pegboard world uses a batch executable to start the ROS and Gazebo using a roslaunch. The batch uses all Gazebo environment variable contained in the workspace (e.g., not global default definitions such as GAZEBO_MODEL_PATH).

First, we determined the root folder of the Gazebo pegboard world using a Windows DOS batch script trick. Unfortunately, there are always a number of tricks with any scripting language, either bash, DOS, or powershell. Navigating paths using local variables in DOS can be tricky. Listing **??** shows the use of the “FOR” DOS command that allows one to iterate over a list of items and run commands on each of them. Below is an example to set the "root" local batch variable to the current directory ('*cd*') parent (i.e., "..").

One trick to make this folder navigation easier is to use the "usebackq", which will remove the double quotes around items with the 'cd' command (but there are none). This is useful if the file path has spaced in it that need to be double quoted.

Understanding the location of the workspace root folder is unnecessary to define the Gazebo environment variables. Listing 11 shows we first define Windows environment variables to define the environment variable "aprs" which points to the Gazebo SDF world file, the Gazebo model folder and then the Gazebo plugins folder (for our gripper plugin). We then use the Windows "set" DOS command to define the required Gazebo environment variable GAZEBO_MODEL_PATH and GAZEBO_PLUGIN_PATH.

Listing 10: Batch file setting Gazebo environment variables for pegboard world

Once we have the Gazebo environment setup, we can then use roslaunch to start Gazebo pegboard world. roslaunch is a ROS 1 XML script command to start a ROS master, that is the standard method for starting ROS nodes and bringing up robots in ROS. To start a Gazebo world, we have defined a gazebo.launch file under the bin folder in the bin

launch folder that contains all the necessary parameters to start the Gazebo pegboard world simulation[3]. Again we use a Windows DOS script method to retrieve a folder from a 'cd' which is evaluated (executed) by the DOS shell before the main command is executed, and the output of that execution is used by that command.

Listing 11: Using roslaunch to start the Gazebo pegboard world

The complete Windows batch script to Launch the Gazebo pegboard world with Fanuc robot using ROS 1 noetic is shown in A.1.

A.2 Experiment F/T ROS Workspace

It appears as if most of build of ROS noetic with Visual C++ 2019 is for release configuration. Since one would like to provide debug symbols with a release build, this can be done using the $/DEBUG$ property flag in catkin_make CMakefile.txt as shown in Listing 12, so you can easier debug a release build application[4].

Listing 12: Catkin Property to Build a Visual C++ Executable with Debug Symbols

A.3 Running Robot Peg-in-hole insertion Simulation

This section briefly describes the basics of running peg-in-hole insertion simulation software. The instructions assume a reasonable understanding of ROS and Gazebo. Further, we assume you have installed the Microsoft Windows noetic distribution into `C:\opt` following the instructions found here.

[3] `http://gazebosim.org/tutorials?tut=ros_roslaunch`

[4] `https://docs.microsoft.com/en-us/cpp/build/reference/debug-generate-debug-info?view=msvc-160`

In addition, the instructions make the use of Windows Terminal to launch multiple ROS workspace nodes mandatory.

1. Install by going to Microsoft Store website and searching for Windows Terminal. Install. Open Windows Terminal from Start menu. Go to the settings under the down arrow on the top bar.

2. Create a new types of Windows, click the downward arrow button and select “+Add new profile” and add “ROS Noetic” terminal.

3. Listing 13 shows the text to copy into ROS command line:

   Listing 13: Text to enable Visual C++ 2019 and ROS to be used as maketools

4. Helps to change starting directory to C:

5. Additional Windows Terminal installation instructions found here.

Using Windows terminal configured for ROS, we can now spawn two terminals to handle the Gazebo pegboard world workspace node and the peg-in-hole experiments workspace node.

Listing 14: TERMINAL 1

Listing 15: TERMINAL 2

where the commmand line variable for rosrun are defined as:

and

B Instructions for using the Gazebo Robot F/T Sensor Plugin

The Fanuc LRMate is an articulated robot of the configuration shown in Figure 15a. The Fanuc LRMate uses a roll-pitch-yaw wrist configuration as shown in Figure 15b. A roll-pitch-yaw wrist is a popular robot configuration in that it provides full range of orientation of the end effector. Note, various configurations are possible in achieving the same robot pose, by having the elbow or shoulder either “up” or “down”. In our case study, we assume a two finger parallel jaw gripper that will grab the pegs. We also employ a Gazebo force torque sensor plugin that detects and reports the different forces that are applied on the robot wrist for the 3 geometric axes (X-Y-Z). If a zero or little force is measured that means no force from a contact or collision is detected in the wrist. The sensor also detects the torque applied around the 3 different axes.

By providing force/torque measurements, the sensor plugin gives feedback to the robot which can adapt its motion. For example, if the forces increase that means the gripper held peg is in contact with the pegboard. Once the sensor is reporting a sufficient amount of force torque, the robot can not do a spiral or raster search for the hole. It is possible for the F/T sensor to measure force on a specific axis other than the Z axis, but we will assume the peg is moving in downward motion in the Z axis to initiate contact with the pegboard. once the peg is in

Pics/robotwristconfiguration.jpg

(a) Articulated Robot Configurations

Pics/rollpitchyaw.jpg

(b) Wrist Roll Pitch Yaw Rotations

Figure 15: Robot F/T Configuration

contact with the pegboard the downward motion can stop and a sideways or spiral motion maintaining a constant force can be performed.

Adding the Gazebo force/torque sensor to joint 6 of the Fanuc robot is based on the tutorial found here [77]. The following modifications described in Listings 16 and 17 were made to fanuc_lrmate200id.urdf

Listing 16: Modifying Fanuc URDF Gazebo Reference for Joint 6

This URDF adds the F/T plugin to joint 6 of the Fanuc robot.

Listing 17: Adding F/T Sensor to Fanuc URDF Joint 6

C Transform Meshes

INSTALLATION Install jetbrains pycharm (or Python IDE of your choice) Set python interpreter: add 3.7 so that its part of Pycharm NOT Windows https://www.jetbrains.com/help/pycharm/configuring-python-interpreter.html#interpre

ImportError: No module named numpy-stl > pip install numpy-stl This is the major STL mesh analysis library.

Setting command line args:

In the folder PyAnalyzeMeshes is a Python script to analyze and make minor changes to STL meshes. It is based on the python library stl.Mesh (https://pypi.python.org/pypi/numpy-stl/1.3.5). Instructions for installing it are there.

It will automatically generate a mesh analysis report containing volume, COG, Inertial Frame, and min/max xyz. For gears I tried to center and translate the mesh so that the minimum z is 0, and when this is done it automatically generates a new file name with "$_{C}entered”or”_{Z}eroZmin”or”_{Z}eroZmax”or”_{R}otate”axesappendedtooriginalfilenam$

AnalyzeMeshes.py use stl-mesh python library to

Example use of AnalyzeMeshes.py

Figure C shows an example of mesh analysis output log stored in AnalyzeMeshes.ini. It produces a log of the

and more ini sections based on number of file titles. So each section corresponds to a file title found in a folder or the filename title.

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