Identification of Industrial Robot Arm Work Cell Use Cases and a Test Bed to Promote Monitoring, Diagnostic, and Prognostic Technologies

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ABSTRACT

The National Institute of Standards and Technology (NIST) is performing research to advance the state of the art in monitoring, diagnostic, and prognostic technologies (collectively known as prognostics and health management (PHM)) to enhance decision-making at the factory floor to promote smarter maintenance and control strategies. One specific thrust in this hierarchical research is focused at the work cell level. A robot system is the focus of this research level where the manufacturing community would benefit from measurement science (e.g., performance metrics, test methods, reference datasets, software tools) to design, deploy, verify, and validate PHMC technologies aimed at a robot system work cell. NIST's identification of representative manufacturing robot work cell use cases will provide the foundation for which it will construct its own physical test bed. The test bed is designed to emulate the chosen robot system use case and afford sufficient flexibility to add, subtract, or upgrade components and capabilities to be commensurate with common industrial practices. This paper presents various use case options that NIST has considered and highlights the one that will be the foundation of the physical test bed. Additionally, the initial test bed design is introduced.

1. INTRODUCTION

Manufacturing factory floor operations are becoming increasingly complex, yet more efficient and/or flexible with the inclusion of advanced technologies. Keeping factory floor technologies at efficient operations requires thoughtful maintenance and control practices (Lee, Ghaffari, & Elmeligy, 2011) (Jin, Siegel, et al., 2016). One such factory floor level technology that may bring greater efficiency, yet add more complexity and maintenance (dependent upon what system or technology the robot is replacing) is the industrial robot system. They are becoming more widely used within many manufacturing environments including those that build automobiles, aircraft, and consumer-electronic goods (DeVlieg, 2010) (Kahan, Bukchin, Menassa, & Ben-Gal, 2009) (Kusuda, 1999) (Zwicker & Reinhart, 2014). Maintenance practices are critical to keeping industrial robot systems running at necessary efficiencies and accuracies to enable manufacturing process productivity and quality targets. This effort defines a robot as an industrial robot and a robot system as an industrial robot system according to definitions specified in ISO Standard 8373 (International Organization for Standardization, 2012) . These definitions are:

- 2.9 Industrial Robot – automatically controlled, reprogrammable (2.4), multipurpose (2.5), manipulator (2.1), programmable in three or more axes (4.3), which can be either fixed in place or mobile for use in industrial automation applications
- 2.15 Industrial Robot System – system comprising industrial robot (2.0), end effectors (3.11) and any machinery, equipment, devices, external auxiliary axes or sensors supporting the robot performing its task.

Prior efforts have provided case studies to determine the current state of maintenance practices within manufacturing environments (Jin, Weiss, Siegel, & Lee, 2016) (Helu & Weiss, 2016). Both large and small- to medium-sized manufacturers (SMMs) were examined. In short, the case study findings illuminated that both large manufacturers and SMMs would benefit from both advanced maintenance and control strategies with respect to their manufacturing operations, including those featuring robot systems.

The U.S. National Institute of Standards and Technology (NIST) has developed the *Prognostics, Health Management, and Control* (PHMC) project to generate measurement science products (e.g., performance metrics, test methods, reference datasets, software tools) to promote the design, deployment, verification, and validation of monitoring, diagnostic, and prognostic technologies at the factory floor level to enhance decision-making to yield smarter maintenance and control strategies (National Institute of Standards and Technology, 2017). This paper documents NIST's efforts to further develop use cases and construct a test bed to enable the development of performance metrics, test methods, reference datasets, use case scenarios, and software tools for an industrial arm robot work cell. Section 2 presents NIST's research focus with respect to industrial arm robot system PHMC. Section 3 highlights several use cases and key characteristics that have been identified through discussions and site visits with various manufacturers. Section 4 details the initial test bed use case configuration. Section 5 provides information on major components being used in the initial test bed configuration. Lastly, Section 6 concludes the paper and discusses future efforts.

2. RESEARCH FOCUS

NIST's PHMC project is influenced by input from manufacturing stakeholders including end-users, technology integrators, technology developers (both hardware and software), academic institutions, and other government organizations (Pellegrino, Justiniano, Raghunathan, & Weiss, 2016) (Brian A. Weiss et al., 2015) (Jin, Siegel, et al., 2016). Part of this input is coming from SMMs (Helu & Weiss, 2016). NIST's research approach can be broken down into three levels:

- Component Level – Machine Tool Linear Axes Diagnostics and Prognostics (Gregory W Vogl et al., 2017)
- Work cell Level – Health and Control Management for Robot Systems (Qiao & Weiss, 2017) (Brian A Weiss & Qiao, 2017)
- System Level – Manufacturing Process and Equipment Monitoring (Helu & Hedberg, 2015)

Manufacturers have successfully deployed industrial robots in a variety of configurations to accomplish a wide range of tasks. In the past, it was common for a robot to perform the same operations throughout its lifespan. In today's evolving economy where manufacturers need to be responsive to ever-changing consumer demands, robots are often reconfigured to perform a wide range of tasks over their lifespan {Link, 2016 #629}. Or a robot may be called upon to vary its operations on a regular basis. For example, a robot may be asked to use multiple tools during its "work day" where it could be installing vehicle seats in one instance with one type of end effector and then placing a windshield onto a car frame with another type of end effector {Wired, 2013 #630}. These changing demands make it challenging to ascertain the robot arm's health. Likewise, the integration and change-over of technology, whether planned or unplanned, makes it challenging to determine the health degradation of the overall robot system or work cell.

Installed robot systems must be robust, especially when used in high-volume applications, and must undergo preventative (or predictive) maintenance to ensure their performance reliability. Robot systems are becoming more complex, especially with the inclusion of additional sensors (to offer more awareness and intelligence to better respond to faults and failures), safety systems (to promote more operations where robots and humans work in close proximity to one another), and end-effector variants (this is highlighted when a robot is capable of quick-changing tools allowing it to increase its operations). More industries are utilizing robotics to perform a wide-range of operations. Monitoring may be leveraged to minimize the occurrence of faults and failures. This is becoming more critical as a robot system increases the diversity of its operations. Data captured across multiple cycles (of differing activities or parameters) is less likely to support "apples-to-apples" comparisons.

NIST's work cell research requires the identification of numerous use cases that can be represented in test methods that are realized within a physical test bed. NIST is constructing such a test bed where the initial configuration should be complete and active by late 2017. The construction of this test bed will promote development of measurement science including performance metrics, test methods, reference datasets, and software tools that will ultimately support open standards and guidelines.

3. USE CASES FOR ROBOT SYSTEMS

Designing appropriate use cases for which to build the health and control management of robot systems research upon is critical to generate output that is relevant and valuable to industry. Considerable effort has been put forth to understand numerous industrial arm robot system use cases that are currently active in industry. This section highlights several of those use cases including those used by large and/or SMMs. This effort took shape through numerous case studies that the NIST research team undertook. Several case studies were documented as a joint effort between the NIST, the University of Cincinnati, and the University of Michigan – Ann Arbor (Jin, Siegel, et al., 2016) (Jin, Weiss, et al., 2016). Likewise, this research was also complemented by case studies that focused on SMMs (Helu & Weiss, 2016). A use case for the overall project has been developed that brings together the component, work cell, and system research levels. This use case involves a mix of machine tools, robot systems, and inspection equipment that must interact together to perform a process (Brian A Weiss, Helu, Vogl, & Qiao, 2016). This use case would support a mix of diverse manufacturing technologies and is represented in Figure 1.

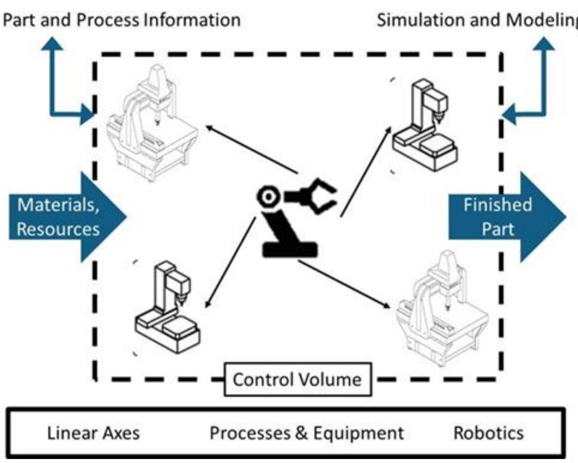

Figure 1. Overall Use Case for NIST PHMC Research (Brian A Weiss et al., 2016)

The remainder of this section outlines numerous use cases that the PHMC team aims to represent in its research to ensure relevance to the manufacturing community's needs. By no means do the highlighted use cases represent an exhaustive list; these use cases are indicative of common robot work cell activities and/or present challenges making advanced monitoring, diagnostics, and prognostics advantageous to their overall effectiveness.

3.1. Time-Based vs. Event-Based Tasks

Every robot task and sub-task is executed based upon a specific lapse in time, the occurrence of an event, or combination thereof. For this effort, time-based tasks can be defined as a robot waiting a set period of time between tasks or from an idle state to an active state. An example of this could be a robot holding a freshly-glued panel in place for a specific time to ensure sufficient adhesion between the set surfaces. An event-based task is defined as a task that is performed only after the robot has received an input, whether it be from an operator, sensor, or other automation signal before proceeding to its next task. An example of an event-based task would be a robot waiting for an input from a proximity sensor alerting the robot that a box is present and ready to be moved into another location. A hybrid task is one that is governed by both the completion of an event or lapse of a specified period of time. For example, a robot that is holding two glued parts together, may have to hold the pieces together for a minimum amount of time until it releases its grip and repositions itself to hold two more pieces together. However, if the subsequent parts are not ready to be mated, then the robot could idle until a 'parts ready' signal is received. The NIST robot work cell use case will feature a combination of time-based and event-based tasks to ensure that a range of variations are represented in the course of verifying and validating PHMC technologies that inform on the health of the work cell. For example, many manufacturers, both large and small, leverage industrial robot systems to move objects from one position to another position within a given work volume. Industries, including those within the automotive and aerospace supply chains, and consumer-electronic goods, use industrial robot arms for a range of material handling operations such as part transfer, packaging, and palletizing. These operations include both time-based and event-based tasks.

3.2. Positioning vs. Compliance vs. Allowance

All industrial robot operations feature some type of movement given that an industrial robot is defined to include a manipulator and is programmable (i.e., controllable) in at least 3 degrees of freedom. Given this definition, all industrial robots are capable of being positioned at specific locations within their work volume. The accuracy of this positioning capability is governed by numerous factors including a robot's physical specifications (e.g., motors, gears, joint encoders) and controller (at minimum, the robot's specific controller).

In many operations, robot positioning is supplemented by additional active or passive motion capabilities to increase the robot's accuracy and/or increase task success. Positional allowance in this context is defined as the acceptable positional relationship deviation from nominal between two components. In every interaction between a robot's end effector and a work piece, and a work piece and fixturing, there is positional deviation allowance (acceptable deviation from nominal relationship). For example, a robot is to insert a round peg into a round hole with twice the pegs diameter (e.g., the peg has a diameter of 2 cm while the hole has a diameter of 4 cm). The nominal insertion position of the peg is the center of the hole. However, the robot may not achieve the position precisely, where it can be off center by less than the radius of the peg. The insertion is still successful because there was allowance (clearance in this case) in the hole that the peg was inserted in.

When the positional allowance between a tool and a workpiece is less than the accuracy of the robot performing the positioning, or information provided to the robot for positioning (e.g., assumed positions, imprecise sensor information), compliance is required to ensure task success. There are two forms of compliance, passive and active. Active compliance is typically enabled by external sensors providing position feedback (e.g., force, vision, distance sensors) and actuation positioning actuators (possibly the robot drives themselves) and can be programmed to automatically occur within a given operation. Active compliance can be considered micro-positioning once a robot has positioned itself within a designed area. Passive compliance is enabled by flexible components which, typically undergoing elastic deformation and cannot be programmed (e.g., spring-loaded break away, flexible brushes). Compliance is often used to augment robot positioning to create an allowable relationship between the end effector and workpiece or workpiece and fixture when the workpiece is being positioned by the robot.

A machine tending operation can be an example of a robot positioning task that highlights both active compliance and allowance (see **Error! Reference source not found.**). Consider the machine tending task that requires a robot to pick up parts from an incoming conveyor belt and place them on a fixture within a machine tool. In this specific example, an industrial robot arm, with an attached parallel gripper, is mounted to a rigid base where incoming parts, the machine tool's work fixture, and the finished part's outgoing mode of transport (to the next station) are within the robot's work volume. Material handling operations are typically not high-precision operations in that the opening and/or operations of the end-effector and the interaction between part and fixtures provide allowance for positional deviation from nominal. The part in question is a 50 cm cube and needs to be picked by the parallel gripper which opens to 60 cm. Incoming parts (e.g., cubes) on the conveyor belt are spaced approximately 100 cm apart and are resting in a random orientation. The robot knows the approximate (assumed) location of the part on the incoming conveyor belt and after each part is removed from the conveyor belt, it automatically moves 100 cm forward. The machine tending operation begins with the robot moving to a position above the assumed position of the part. Once the robot and conveyor are in position for the next pick, an external vision system (compliance sensor) measures the part's precise position and orientation (more precise then the assumed position) and automatically provides this information to the robot's controller so the robot may refine its location, complying to the part location. Once the robot is positioned based on the vision system's information, the robot can position the gripper jaws around the part and close to complete the pick operation. Because the part can slide freely on the conveyor top while the gripper jaws are closing, the lateral position allowance in the gripping direction is +/- 5 cm from center, and imperfect positioning and orientation below the allowance will not cause the pick to fail. This external sensor's feedback offers an automated means of compliance to increase the accuracy of the task and reduces the allowance needed. Even with the vision system's additional information, the +/- 5 cm of allowance provides an additional margin of error for the task to be successful simply by closing its jaws.

Compliance and allowance are seen in other operations. The use of vacuum grippers offer another means of allowance in material handling operations. A vacuum gripper may have a suction area of x cm^2 while the top of the box it is picking up has an area of y cm^2 where $y > x$. It is likely optimal for the gripper to pick the box from its center, yet the gripper can still be successful in picking up the box if it is slightly off-center (the robot system may not be successful in moving or placing

Figure 2. Machine-tending Operation (Fotolia)

the box if its off-centered position causes it to become unbalanced within the gripper).

Industrial arm robot systems are supporting more precise operations, when paired with active compliance end-effectors and/or sensors that promote a finer degree of positioning as compared to the robot's movement, alone. In some instances, this capability is allowing the overall work cell to outperform human counterparts in terms of accuracy, repeatability, and reliability. Another example of an active compliance end-effector would be a complementary drilling tool mated to the end of a robot. The robot moves the drill to an exact location near the surface it needs to drill, the end-effector drill would provide the necessary plunging movement and force to produce the desired hole. When the position of the hole must be more precise than the robot is, the end-effector may be capable of further positioning of the drill with onboard actuators (e.g., servos and lead screws) (once the robot has placed the drill in an approximate location) and performing the drilling/plunging task.

Overall, many common manufacturing industrial robot operations are enabled by some combination of positioning, compliance, and allowance. Welding, gluing, 3D-printing, fastening, and mating operations highlight many successful examples of industrial arm robots, external axes, external sensing, supporting automation, and controllers working in harmony. However, each manufacturing process, and constituent components, mentioned in this section are subject to some form of health degradation over time. If left unchecked, this health degradation will compromise the success of the operation impacting quality, productivity, etc. when allowances are exceeded and limits of compliance are reached.

3.3. PHMC Robot Work Cell Use Case

All NIST use cases involve an end-effector on the robot arm, the robot controller, a human-machine interface (HMI, which may be directly integrated with the robot controller), and some level of safeguarding. Some of the robot work cell configurations will include additional elements that range from a programmable logic controller (PLC), sensors (e.g., camera systems, or other sensors measuring part presence or specific location information), external axes, and supporting automation (e.g., conveyor belt bringing parts into the work cell or taking away completed parts and actuated fixtures). The presence, or lack thereof, of these elements is influenced by many factors including complexity of the desired process, number of robots, variability of the process, number of system inputs and outputs (sensors and actuators) and proximity of human operators.

The initial NIST PHMC use case consists of two robots working together to accomplish a specific operation (Brian A Weiss et al., 2016). One robot is configured for material handling (see Figure 3) and is used to transport parts into and out of the second root's work volume. The second robot performs a simulated precision operation (e.g., the robot touching the center of a part with a tool tip that leaves a mark on the part). This precision operation is intended to represent a precise manufacturing operation (e.g., welding, machining). A supervisory PLC is used to monitor and coordinate the movement between robots. When running nominally, the PLC will manage the status of each part in process and command both robots to take particular actions. Each action the PLC can command a robot to do is programmed and stored on the individual robot controllers. This includes Cartesian waypoints and motion profiles.

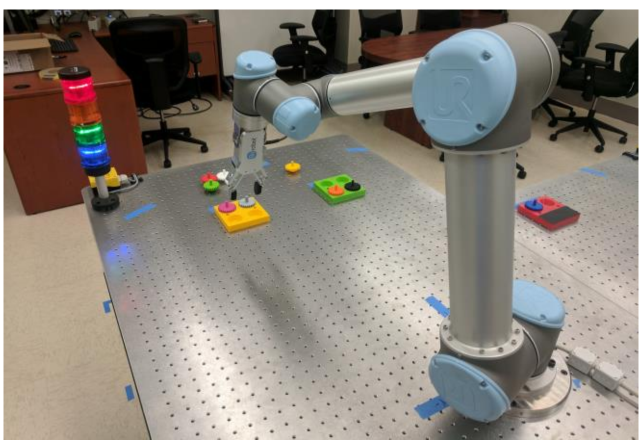

Figure 3. PHMC Material Handling Robot

The development of this test bed will allow researchers to develop PHMC methods on real equipment and verify that methods requiring physical components such as test artifacts can be integrated into a real process and perform as intended. The test bed will also enable the examination of hardware resilience under fault and failure conditions, provide the ability to stress specific elements within the work cell, and simulate various faults and failures in certain components to understand how these errors propagate through the system and impact the overall work cell.

Edge cases may also exist in a real system that would be hard to implement in a simulation even if they are known. The availability of information and limits of communications technologies are real constraints in implementing PHMC in existing systems. By using a physical test bed all of the limits of the work cell components must be dealt with ensuring a solution that is applicable to manufacturers.

4. TEST BED CONFIGURATION

The robotics test bed at the NIST is a reconfigurable work cell with multiple robots performing different tasks. This work cell allows NIST to evaluate the use case presented in Section 3 and future iterations of the use case. Figure 4 shows the PHMC robot work cell, still under construction.

Figure 4. PHMC Robot Work Cell (Under Construction)

The initial configuration for the test bed includes manufacturing relevant equipment including two industrial robot arms, a task-specific tool on each robot, fixtures to hold test parts and artifacts, a supervisory PLC, a human-machine interface, safety systems, representative parts and test artifacts for the robots to interact with and optical tables to fix the equipment to in a controlled way. Future configuration plans include the addition of a conveyance system(s) and a vision system(s).

One robot will be configured for material handling operations with a gripper type end-effector. The second robot will be configured to perform a precision operation with the chosen end-effector and test parts. Parts being moved and operated on inside the work cell will feature geometries that make them representative of parts typically found in the use cases outlined in Section 3. It is anticipated that test artifacts, engineered geometries designed to aid in test methods currently under development, will also be present in the work cell.

The material handling robot will perform pick and place operations including moving parts from an input area to in-process work fixtures. Once parts are placed in/on the work fixtures, the second robot will interact with the part in a specified precise manner. When the precision operation is completed, the material handling robot will then move the completed part to an output. The general layout for this can be seen in Figure 5. A PLC will be used to monitor all work cell input and output sensors beyond integrated robot and end effector sensors and coordinate these tasks Specific sensors are still being determined for integration and monitoring within the work cell and could include presence detection and distance measurement sensors. It is anticipated that in addition to moving the representative parts around and performing simulated high accuracy tasks, the material handling and precision operation robots will also interact with test artifacts during the execution of test methods.

A HMI consisting of a digital monitor(s) and physical buttons will be built to provide a means of operator control and feedback. The HMI will contain operator controls and provide system status information. System status information will include process control information as well as health state information that is obtained when executing test methods under development.

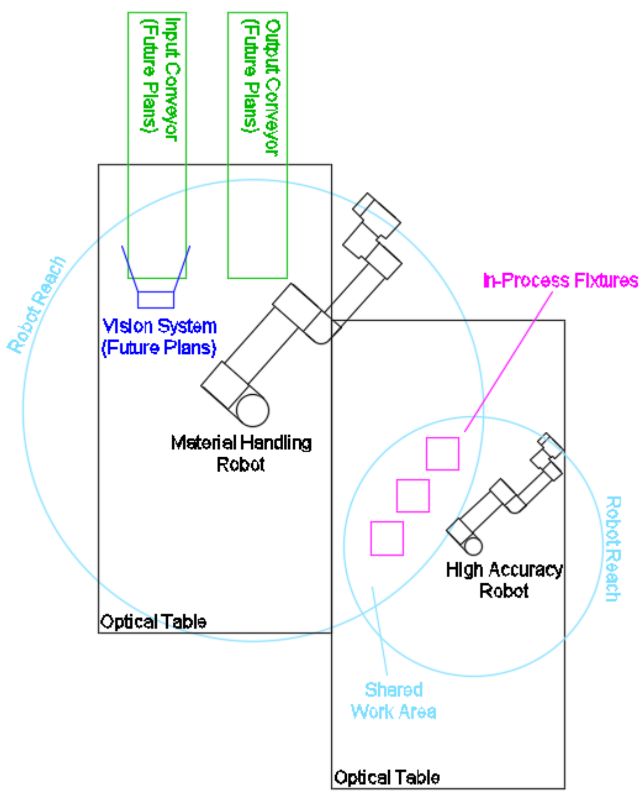

Figure 5. PHMC Robot Work Cell (Upon Completion)

Numerous configuration constraints exist on the test bed outside of the PHMC project's control. One of these constraints is the physical size of equipment being used. The robots and all other equipment must safely fit into the available lab space. This limited robot selection to the small-mid size range. Other constraints such as door openings and elevator size were taken into consideration when selecting optical tables and other large pieces of equipment.

Though the robots that will be used in the PHMC lab are relatively small (in the industrial robot domain), the use case, robots, and processes are scalable to other sizes of equipment found in industry. Using small robots will allow for optimal physical access during integration and development. Researchers in the lab will have physical access to all components of the work cell without the need for additional access and safety equipment such as ladders and fall protection. Likewise, smaller benchtop robots would force researchers to work in limited space, adding additional complexity in integration, reducing flexibility in end effector and sensor selections and configurations.

5. TEST BED COMPONENTS

Each of the following test bed components are actively being specified or integrated (where the specification and procurement has been completed). It is important to note that each of the following components is a potential source of faults or failures within the work cell. These potential faults and failures are not discussed in this publication, yet will be discussed in future work.

5.1. Industrial Robots

Two lightweight, industrial, six degrees of freedom (6DOF) robotic manipulators comprise the robotic component of the test bed. One robot has a rated lift capacity of 3 kg and a reach of 0.5 m, while the other has a rated lift capacity of 5 kg and a reach of 0.85 m. These robots are chosen because they are (1) 6-DOF articulated arm robots used in industry, (2) flexible robots that can be integrated quickly in the PHMC robotics test bed, allowing the focus to be on test method development, (3) The physical size of the robots work well in the laboratory environment. Larger robots would not be able to exercise a full range of motion in the PHMC Laboratory, While smaller robots would make integration of additional sensors more challenging, (4) used in multiple labs at NIST and an in-house expertise is established allowing for technology transfer and sharing of resources between research projects, (5) designed to be used safely among humans with minimal additional safety requirements, limiting the need for expensive safety equipment, costly integration, and complex operating procedures.

5.2. End-Effectors

The On Robot RG2 Gripper was selected as the end effector for the material handling operation in the initial test bed configuration (Figure 6 shows the RG2 mounted to the UR5 within the PHMC test bed). The RG2 is relatively low cost and comes with a software package for URs making it quick to integrate and operate., limiting integration time and complexity. The RG2 is an electrically actuated gripper that is grip force and/or position controllable. This allows the gripper to be used in both time-based control and event-based control schemes. The gripper is capable of being controlled though the robot controller or the PLC.

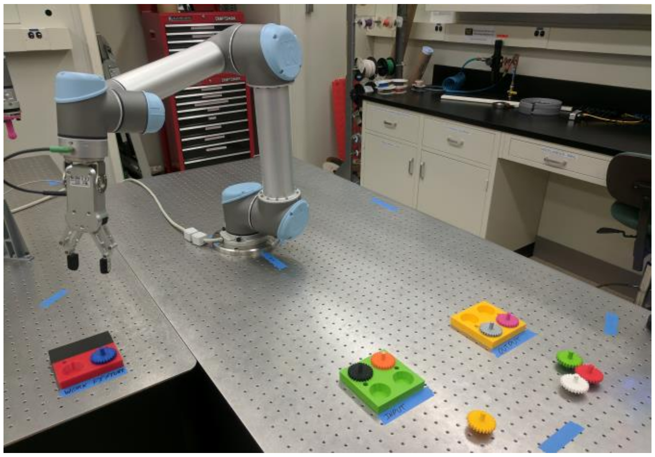

Figure 6. Material Handling Robot with an RG2 Gripper

A fixed end effector was selected for the simulated precision operation in the initial configuration (This end effector is still in the design stages). The end effector will have a feature(s) that will allow for test method verification. These features may include visual fiducials that can be tracked, or specific geometry that interacts with parts and artifacts. Additional end effectors may be integrated into the PHMC Robotics Test Bed in future configurations.

5.3. Fixture(s)

Fixtures for the test bed will be manufactured at NIST to work with the parts and artifacts being used. Extruded polymer 3D printers will produce the test bed fixtures. This will allow for quick turnaround on design variations necessary in the development of test methods.

5.4. PLC/Process Controller

A Beckhoff PLC was selected to be the PHMC Robotics Test Bed process controller. The PLC was chosen for supervisory process control over using the robot controllers (to communicate with each other directly) because it is a flexible hardware and software device that can be reconfigured for use in future test bed configurations. A PLC also allows for greater flexibility in the amount and types of sensors and data that can be monitored and recorded throughout a process. The selected platform is sufficient to control multiple test bed configurations while running NIST-developed software without the need for additional computers, wiring, and communication integration. The PLC will also serve as the historian, recording process information, raw sensor data and output data from PMHC test methods under development.

5.5. HMI

The initial configuration of the test bed will include a simple HMI consisting of a few buttons and switches used to start and stop processes, acknowledge faults, and select operating mode along with a visual display which will be used to visualize system status. This display may also display data related to PHMC test methods being developed on the test bed. In the initial configuration, the visual display will be managed by the PLC. Future plans include the incorporation of a standalone HMI integrated with the test bed through the PLC.

5.6. Safety Systems

Industrial safety equipment including safety-rated sensors and a safety PLC will be used to protect those working around the test bed. The safety sensors will include safety laser scanners, safety floor mats, emergency stops, and visual indications of safety status. The system safeguards the work cell in compliance with the specifications in ISO 10218-2:2011.

5.7. Additional Work Cell Elements

Other elements are present within the work cell, are in the process of being added, or are being planned for future configurations.

- Optical tables - currently present within the work cell. Optical tables were chosen as the mounting platform for the test bed because they provide a stable base, and can be used to support a convenient common coordinate system for the robots and sensors.
- External Sensors – in the process of being added and being planned for future configurations. In the initial configuration of the test bed, only sensors which are needed to perform the use case and collect health information deemed valuable are used. This includes monitoring of sensors embedded in the robots and end effectors and operator controls. As the work cell becomes more “intelligent” more sensors will be added. Future plans include additional sensing to allow the material handling robot to accurately pick a randomly placed part on a moving conveyor. This may include a vision system or other part detection sensors.
- Conveyor System(s) – being planned for future configurations. A conveyor system will be used to input raw parts and output finished parts to and from the work cell.

6. CONCLUSION

The fusion of emerging technologies with innovative manufacturing operations has increased the complexity of processes and equipment found on the factory floor. To maintain their competitive advantage, manufacturers must minimize both the planned and unplanned downtime of their manufacturing processes and supporting equipment. PHMC is offering the manufacturing community a way of enhancing monitoring, diagnostic, and prognostic capabilities to stay "one step ahead" of faults and failures.

To promote greater viability and adoption of PHMC technologies, NIST is conducting research at the component, work cell and system levels. NIST's PHMC research of robot work cells focuses on current industry challenges in maintaining the health of industrial arm-based automated processes. NIST has identified representative manufacturing robot work cell use cases. These use cases are serving as the foundation for NIST to construct its own use case and physical test bed. The initial configuration has been specified and is being integrated. In parallel, additional capabilities (e.g., external sensors) are still being specified and are expected to be integrated in the future. This will provide a sufficiently flexible and expandable test bed where PHMC methods can be developed, verified and validated and reference datasets can be collected. NIST is actively constructing the test bed and is expected to have the initial configuration complete and operational in late 2017. As the test bed is being constructed, test methods are being designed that will leverage the test bed's capabilities and support the further development of the use case. These test methods will be presented in future work.

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REFERENCES

Abdi, H., Nahavandi, S., Frayman, Y., & Maciejewski, A. A. (2012). Optimal mapping of joint faults into healthy joint velocity space for fault-tolerant redundant manipulators. *Robotica, 30*, 635-648. doi:10.1017/s0263574711000671

DeVlieg, R. (2010). Expanding the use of robotics in airframe assembly via accurate robot technology. *SAE Int. J. Aerospace, 3*(1), 198-203.

Hedberg, T., & Helu, M. (2016). Smart Manufacturing Systems (SMS) Test Bed. Retrieved from http://www.nist.gov/el/facilities_instruments/smstestbed.cfm

Helu, M., & Hedberg, T. (2015). Enabling smart manufacturing research and development using a product lifecycle test bed. *Procedia Manufacturing, 1*, 86-97.

Helu, M., & Weiss, B. A. (2016). *The current state of sensing, health management, and control for small-to-medium-szed manufacturers.* Paper presented at the ASME 2016 Manufacturing Science and Engineering Conference, MSEC2016.

Jin, X., Siegel, D., Weiss, B. A., Gamel, E., Wang, W., Lee, J., & Ni, J. (2016). The present status and future growth of maintenance in US manufacturing: results from a pilot survey. *Manufacturing Rev., 3*, 10.

Jin, X., Weiss, B. A., Siegel, D., & Lee, J. (2016). Present Status and Future Growth of Advanced Maintenance Technology and Strategy in US Manufacturing. *International Journal of Prognostics and Health Management, 7 (Special Issue on Smart Manufacturing PHM)*(Sp5), 18.

Kahan, T., Bukchin, Y., Menassa, R., & Ben-Gal, I. (2009). Backup strategy for robots' failures in an automotive assembly system. *International Journal of Production Economics, 120*(2), 315-326. doi:http://dx.doi.org/10.1016/j.ijpe.2007.09.015

Kusuda, Y. (1999). Robotization in the Japanese automotive industry. *Industrial Robot, 26*(5), 358-360. doi:10.1108/01439919910283786

Lee, J., Ghaffari, M., & Elmeligy, S. (2011). Self-maintenance and engineering immune systems: Towards smarter machines and manufacturing systems. *Annual Reviews in Control, 35*(1), 111-122. doi:10.1016/j.arcontrol.2011.03.007

Malinowski, M., Beling, P., Haimes, Y., LaViers, A., Marvel, J., & Weiss, B. (2015). *System Interdependency Modeling in the Design of Prognostic and Health Management Systems in Smart Manufacturing*. Paper presented at the Annual Conference of the Prognostics and Health Management Society 2015, Coronado, CA. http://www.nist.gov/manuscript-publication-search.cfm?pub_id=918960

National Institute of Standards and Technology. (2017). Prognostics, Health Management, and Control (PHMC). Retrieved from http://www.nist.gov/el/isd/ks/phmc.cfm

Pellegrino, J., Justiniano, M., Raghunathan, A., & Weiss, B. A. (2016). Measurement Science Roadmap for Prognostics and Health Management for Smart Manufacturing Systems. *NIST Advanced Manufacturing Seriess (AMS)*.

Peng, Y., Dong, M., & Zuo, M. J. (2010). Current status of machine prognostics in condition-based maintenance: a review. *The International Journal of Advanced Manufacturing Technology, 50*(1-4), 297-313.

Qiao, G., & Weiss, B. A. (2016). Advancing Measurement Science to Assess Monitoring, Diagnostics, and Prognostics for Manufacturing Robotics. *International Journal of Prognostics and Health Management, 7*, 13.

Qiao, G., & Weiss, B. A. (2017). *Accuracy Degradation Analysis for Industrial Robot Systems*. Paper presented at the ASME International Manufacturing Science and Engineering Conference, Los Angeles, California.

Visinsky, M. L., Cavallaro, J. R., & Walker, I. D. (1994). ROBOTIC FAULT-DETECTION AND FAULT-TOLERANCE - A SURVEY. *Reliability Engineering & System Safety, 46*(2), 139-158. doi:10.1016/0951-8320(94)90132-5

Vogl, G. W., Donmez, M. A., Archenti, A., & Weiss, B. A. (2016). *Inertial Measurement Unit for On-Machine Diagnostics of Machine Tool Linear Axes*. Paper presented at the Annual Conference of the Prognostics and Health Management Society 2016, Denver, CO.

Vogl, G. W., Pavel, R., Archenti, A., Winnard, T. J., Mennu, M. M., Weiss, B. A., & Donmez, M. A. (2017). *Identification of machine tool geometric performance using on-machine inertial measurements*. Paper presented at the 6th International Conference on Virtual Machining Process Technology (VMPT 2017), Montreal, Canada.

Vogl, G. W., Weiss, B. A., & Donmez, M. A. (2014). *Standards Related to Prognostics and Health Management (PHM) for Manufacturing* (NISTIR 8012). Retrieved from Gaithersburg, Maryland, USA: http://dx.doi.org/10.6028/NIST.IR.8012

Vogl, G. W., Weiss, B. A., & Helu, M. (2016). A review of diagnostic and prognostic capabilities and best practices for manufacturing. *Journal of Intelligent Manufacturing*. doi:10.1007/s10845-016-1228-8

Wang, R., Liu, L., & Xu, F. (2008). Research on prognostics technology of robot system. *Machine Tool and Hydraulics, 30*(11), 15-19.

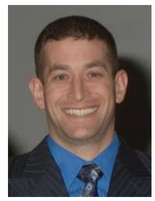
Weiss, B. A., Helu, M., Vogl, G. W., & Qiao, G. (2016). *Use Case Development to Advanced Monitoring, Diagnostics, and Prognostics in Manufacturing Operations*. Paper presented at the IMS2016 - Intelligent Manufacturing Systems, Austin, Texas.

Weiss, B. A., & Qiao, G. (2017). *Hierarchical Decomposition of a Manufacturing Work Cell to Promote Monitoring, Diagnostics, and Prognostics*. Paper presented at the ASME 2017 International Manufacturing Science and Engineering Conference (MSEC2017), Los Angeles, California.

Weiss, B. A., Vogl, G. W., Helu, M., Qiao, G., Pellegrino, J., Justiniano, M., & Raghunathan, A. (2015). *Measurement Science for Prognostics and Health Management for Smart Manufacturing Systems: Key Findings from a Roadmapping Workshop*. Paper presented at the Annual Conference of the Prognostics and Health Management Society 2015, Coronado, CA.

Zwicker, C., & Reinhart, G. (2014). Human-robot-collaboration system for a universal packaging cell for heavy electronic consumer goods *Enabling Manufacturing Competitiveness and Economic Sustainability* (pp. 195-199): Springer.

BIOGRAPHIES



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