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DEVELOPING MEASUREMENT SCIENCE TO VERIFY AND VALIDATE THE IDENTIFICATION OF ROBOT WORKCELL DEGRADATION

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ABSTRACT

Robot systems have become more prevalent in manufacturing operations as the technology has become more accessible to a wider range of manufacturers, especially small to medium-sized organizations. Although these robot technologies have become more affordable, easier to integrate, and greater in functional capability, these advanced systems increase workcell complexity leading to the presence of more fault and failure modes. Given increasing manufacturing competitiveness, maximizing asset availability and maintaining desired quality and productivity targets have become essential. The National Institute of Standards and Technology (NIST) is developing measurement science (e.g., test methods, performance metrics, reference data sets) to monitor the degradation within a manufacturing workcell that includes a six-degree-of-freedom robot arm. Numerous components of the workcell influence the accuracy of the robot's tool center position. Identifying the component(s) responsible for process degradation prior to the process performing out of specification will provide manufacturers with advanced intelligence to maintain or maximize their performance targets and asset availability. NIST's research in robot workcell health promotes workcell component health characterization and develops methods and tools to verify and validate this approach. This paper presents the overall research plan and the efforts to date in developing appropriate test methods, identifying key sources of workcell degradation, and presenting baseline performance data that is leveraged for health assessment.

Keywords: condition monitoring, degradation, diagnostics, industrial robot systems, kinematics, manufacturing processes, manufacturing systems, prognostics, testbed, use cases, workcell.

INTRODUCTION

Robot systems and technologies are becoming more commonplace within manufacturing operations as they increase in capability, become easier to integrate, and become more affordable to industry. Systems are performing a range of operations including high precision tasks [1-4]. Advanced sensing, monitoring, and control technologies have enhanced robot systems and the workcells to which they contribute, to be more productive and efficient. As robot workcells are supporting a larger number of functions or the number of steps within a process presents greater variability, monitoring the workcell's manufacturing process and the health of the physical system becomes more critical. New and complex workcells present greater opportunities for faults and failures to emerge, especially faults and failures that have never been seen before. Monitoring faults and failures of robot workcells has also become more important as robots are used in more collaborative environments in closer proximity to human manufacturing partners; degraded or malfunctioning robots present safety concerns [5].

Maintaining the health of robot workcells is imperative to maximizing asset availability and maintaining minimum levels of productivity and process/part quality. One of the critical metrics that many manufacturers track is *Overall Equipment Effectiveness* (OEE). OEE can be tracked at multiple levels (e.g., at the factory level, assembly line, and equipment level) within a facility and is typically the multiplicative product of productivity, asset availability, and quality [6]. When a process is initiated for the first time, a baseline of performance and health is typically captured. Either that level of performance is acceptable or deemed insufficient where changes are made to increase one or more elements of OEE.

The OEE of a robot workcell is heavily influenced by the reliability (including repeatability) of the robot's positioning [7]. Many manufacturing robot workcells leverage one or more six degrees of freedom (6DOF) industrial robot arms to serve as positioners for end effectors (i.e., tools mounted to the flange at the end of the arm) to achieve a specific task. End effectors range from grippers used in material handling operations, to welding guns, or paint applicators used in very specific activities [2, 8, 9]. In some instances, the robot acts as the operation's macromanipulator, where the end effector serves as the micro-manipulator (e.g., a robot arm with a robotic gripper for in-hand manipulation). Other instances feature the robot as the sole positioner (e.g., a robot with an attached welding gun moving the welder into a specific position or along a trajectory). For these operations to maintain their OEE targets, the robot must be sufficiently reliable and repeatable.

Personnel at the U.S. Department of Commerce's National Institute of Standards and Technology (NIST) are developing the requisite measurement science to verify and validate monitoring, diagnostic, and prognostic capabilities to increase the reliability of manufacturing operations and minimize downtime (both planned and unplanned) [10, 11]. Numerous case studies [6, 12, 13] and the development of relevant manufacturing use cases [14] have been a driving force within this effort. These efforts have resulted in a portion of the project focusing on manufacturing operations of 6DOF industrial robot arms [7, 8, 15].

The goal of the article is to present the latest research plan that is propelling this effort, highlight what has been done to date, including recent accomplishments, and lay out the immediate next steps. One substantial goal of this effort is to provide industry with a low-cost, minimally invasive test method that can be applied within a manufacturing robot workcell to ascertain the health of the components that influence the kinematic chain that, in turn, influence the accuracy of the overall process and resultant product. The kinematic chain is the physical assembly of multiple rigid bodies that are connected to one another and constrained in specific degrees of freedom [7]. A known kinematic chain can be mathematically represented where equations can relate the position of one element to another element (in the chain). An error in a rigid body, or joint, in the kinematic chain can propagate through the rest of the chain creating a positional error.

In addition to disseminating this research in technical articles, it is expected that this effort will provide some of the technical basis for industry-driven standards [16-18]. Even though this specific research effort focuses on 6DOF industrial robot arms, the resultant methods can be adapted to accommodate industrial robot arms with greater or fewer degrees of freedom.

The remainder of this paper is organized as follows. The Background section presents prognostics and health management (PHM) and the critical role it is playing to advance manufacturing operations. The Workcell Research Focus section contains the bulk of this article and is divided into several sub-sections. The Research Motivation section includes the goals of the effort, the motivation, and the expected impact on industry. The Research Plan and Status section discusses the progress that has been made to date. The Current Efforts section discusses the active elements of the research. The Future Work and Conclusions section examines longer term efforts that are being planned to further this work and concludes the paper.

BACKGROUND

The field of Prognostics and Health Management (PHM) focuses on monitoring, diagnostic, and prognostic technologies to enhance maintenance and control strategies to maximize asset availability and maintain productivity and quality targets. With the emergence of technological innovations in manufacturing (i.e., the formation of Smart Manufacturing through greater connectivity of information technology and operations technology), PHM is quickly becoming a critical element within manufacturing operations. PHM has been applied by large manufacturers along with small to medium-sized manufacturers (SMMs) with differing degrees of success [6, 12, 13]. The manufacturing community has leveraged multiple PHM approaches (e.g., data-driven methods, physics-based models, and hybrid methods) to minimize their reactive maintenance activities and optimize their preventive and predictive maintenance efforts [19-22]. Some of the publicly-available PHM practices have been documented in a variety of standards documents [16, 17].

Smart manufacturing presents a complex environment for which PHM is being applied. Prior to smart manufacturing, manufacturing operations and systems were largely disconnected from one another; boundaries were very clear, and relationships among elements were relatively simplistic. The integration of advanced technologies and the connectivity of varying manufacturing processes and equipment across multiple physical locations makes it more challenging to effectively design, deploy, verify, and validate PHM. A manufacturing robot workcell can be considered a complex system of systems and therefore provides an appropriate use case for the application, and verification and validation (V&V), of PHM. A workcell is both an element of a much larger manufacturing operation, and an element that can be broken down into constituent sub-systems, components, sub-components, etc. Successful application of PHM within a workcell requires an understanding of the physical elements within that workcell and how they relate to one another. Maintenance activities are typically performed on physical elements (e.g., replacing a joint, lubricating gears) making it critical to understand how physical elements influence each other, not just in function, but also in health. The decomposition of physical elements of a robotic workcell into a representative hierarchy of elements provides a means of identifying boundaries that can drive maintenance tasks [7]. Furthermore, the physical hierarchy could then be integrated with informational and functional hierarchies to promote a greater understanding of the relationships among elements. This integration would also identify critical metrics and measures of workcell health, both in terms of process health and equipment health [23-25]. As system complexity increases, it becomes more critical to understand the inherent relationships to see how the state of mechanical degradation of physical elements impact process performance.

Recognizing that the robot is a critical element of the workcell, NIST is undertaking another research effort to use vision technology to capture the degradation in accuracy of a robot's tool center position (TCP) while the robot moves through

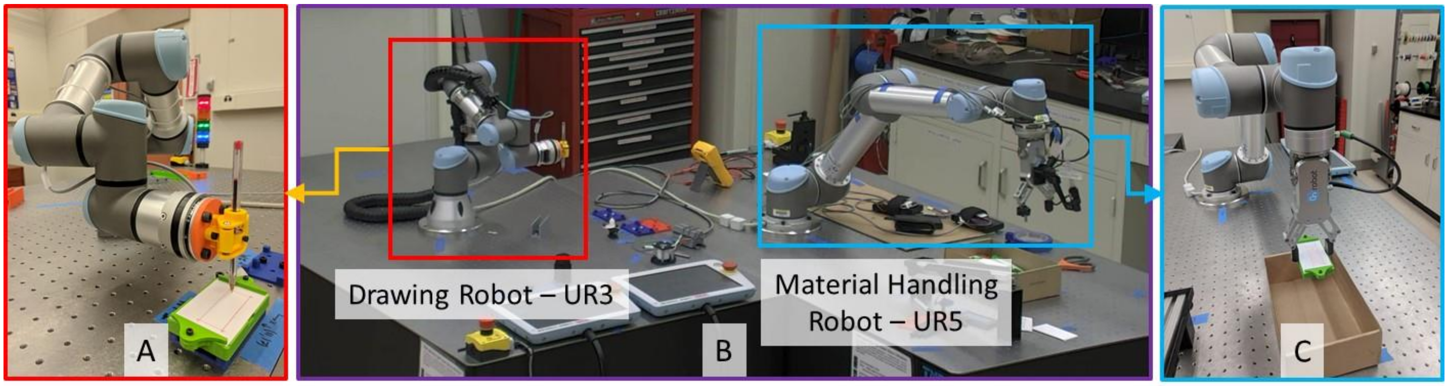

Figure 1: NIST MANUFACTURING PHM RESEARCH ROBOT WORKCELL (B); UR3 DRAWING ON A BUSINESS CARD AFFIXED TO A GREEN PLASTIC PART (BUSINESS CARD HOLDER) (A); UR5 PLACING A COMPLETED PART IN THE OUTPUT BIN (C)

a series of pre-programmed trajectories [26, 27]. The output of this work will provide an understanding of the overall robot arm health along with specific health intelligence of individual joints and constituent components (e.g., motors, encoders, gears). It is expected that this work will complement the efforts of the workcell-level research.

WORKCELL RESEARCH FOCUS

Similar to the definitions listed in the International Organization for Standardization (ISO) Standard 8373 for an Industrial Robot and an Industrial Robot System [28], this effort defines a robot as an automatically controlled, reprogrammable, multipurpose manipulator that is programmable in three or more axes; and the robot workcell as the one or more robots, end-effector(s), and any machinery, supporting automation, external axes, sensors, work fixtures, etc. necessary to accomplish a specific task.

The robot workcell use case leveraged in this research effort is defined as two, 6DOF industrial robot arms working together (shown in Figure 1B with the purple border) to complete a specific task. One robot, a Universal Robots UR5 (shown in Figure 1B and Figure 1C with blue borders), is tasked with performing material handling operations. This robot has a movable gripper mounted to its tool flange where the robot's controller commands the gripper to open and close. The other robot's (a Universal Robots UR3 shown in Figure 1A and Figure 1B with red borders) end-effector is a custom-built holder that contains a pen to support the robot's ability to draw on a surface. The two robot controllers receive higher-level commands from a supervisory Programmable Logic Controller (PLC), and work together to draw a specified design on a business card that is clamped to a plastic part (a green part is shown in Figure 1A). The relevance of this specific use case to that of actual manufacturing operations is 1) the material handling operations of moving a part from an input tray to a work fixture, and then from the work fixture to an output bin, is comparable to part pick and placement common in manufacturing operations; 2) the drawing robot is performing a task comparable to manufacturing path planning operations (e.g., welding or adhesive application) where the robot serves as the lone manipulator for a precision tool and must move along a specific trajectory at a specific speed and accuracy (e.g., vibrations of the end-effector must be within specified tolerances) as it modifies the part; and 3) the overall workcell could be compared to a machine tending operation where a material handling robot places a part within the work volume of a machine tool or an additive manufacturing tool. In this instance, the drawing robot is modifying the part through an additive process. Drawing on a business card, as opposed to drawing directly on the plastic part, allows for quick and cost-effective replacement of the modified part, as opposed to fabricating additional plastic parts.

The workcell's manufacturing process begins with a part being picked up by the material handling robot from the input tray (see Figure 2A and Figure 2B). The material handling robot places (see Figure 2C) the part on one of two fixtures within range of the path planning robot. Once the part is placed on a fixture, the path planning robot begins drawing the target design on the business card within the part (see Figure 3D). While the UR3 is completing this task, the UR5 is moving another part (see Figure 3E and Figure 3F) to the second work fixture, if the work fixture is available and another part has been ordered for drawing. When the path planning robot has completed this task, the material handling robot removes the part from its fixture and deposits it in an output box (see Figure 4G). It is important to note that there are two fixtures within the work volume that can be used by both robots enabling two parts to be 'in process' at the same time. After the UR3 is done drawing on the last part (see Figure 4H), the UR5 removes it from its fixture (see Figure 4I)and moves it to the output bin to complete the production run.

The remainder of this section presents NIST's specific research efforts including the motivation behind this research, the overall research plan, the status of the work, and the current efforts.

Research Motivation

NIST's research plan is built upon addressing the following questions, based upon the Heilmeier catechism (sometimes known as the Heilmeier questions) [29], to articulate the appropriateness and value of the research.

- *What is the problem we are trying to solve? Why is it important?*

The goal is to offer a solution to enable the manufacturing community to verify and validate emerging technologies that monitor, diagnose, and predict the health of robot workcells. As noted earlier, the workcell extends beyond the robot arm including end-effectors, work fixtures, and parts. This involves providing the means to determine the overall health of a robot workcell along with the source of degradations prior to the degradations lowering part and/or process quality, and productivity, out of specification. This would provide the manufacturing community with a test procedure and corresponding performance metrics that would test specific elements (e.g., robot arm, end-effector) of the workcell to determine the degradation, if any, of each element with respect to its influence on process/robot accuracy. Without this capability, manufacturers would be unaware of any degradations within their workcell until it is observed in lower productivity or quality measures, or are observed when a physical component fails.

- *What are we trying to accomplish?*

NIST personnel are trying to develop the requisite measurement science, including test methods, performance metrics, and reference datasets, and contribute to standards to verify and validate emergent technologies that monitor, diagnose, and predict workcell health by examining the physical elements that impact process and robot accuracy. To that end, NIST is conducting multiple research efforts including 1) producing reference datasets from its representative manufacturing workcell to support PHM algorithm development, verification, and validation and 2) developing a minimally-invasive test method to serve as a low-cost solution that will assess the health of a robot workcell and identify the source(s) of degradations prior to their impact on performance targets.

- *How does this get done at present? What are the limitations of current approaches?*

Current workcell degradations are typically detected when either part and/or process quality (e.g., accuracy of a process), or productivity, has fallen below target thresholds. If workcell degradation is detected in advance, it involves

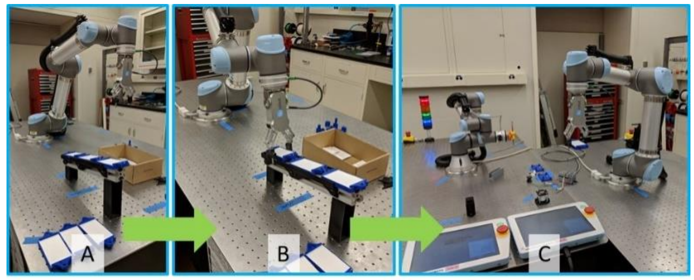

Figure 2. UR5 APPROACHING THE INPUT TRAY (A), PICKING UP A PART (B), AND MOVING THE PART TO AN OPEN FIXTURE (C).

one or more of: costly test equipment, time-consuming processes, and/or test equipment disruptive to the workcell configuration. For example, some manufacturers, especially those that require high precision performance from their robot systems, will use laser-based systems to measure changes in a robot's accuracy. This information is typically used to recalibrate the robot and/or identify changes in accuracy that indicate degraded health.

- *Why should NIST do it?*

The manufacturing community presents a diversity of robot workcells that feature a variety of configurations, robot manufacturers, end effectors, and supporting automation (e.g., linear rails, conveyors). NIST is an independent, neutral third party relative to the manufacturing industry. NIST has a strong history of developing device-agnostic test methods to objectively measure the capabilities of differing implementations [30-32]. NIST's research focus within manufacturing and robotics makes this problem relevant to the current mission.

- *What is new about this approach? Why do you think you can be successful at this time?*

The approach focuses on assessing the kinematic chain that directly impacts the motion that is performed on the part or with the part. The novelty is the systematic and relatively simplistic test method that measures the repeatability of specific elements along the kinematic chain to determine if

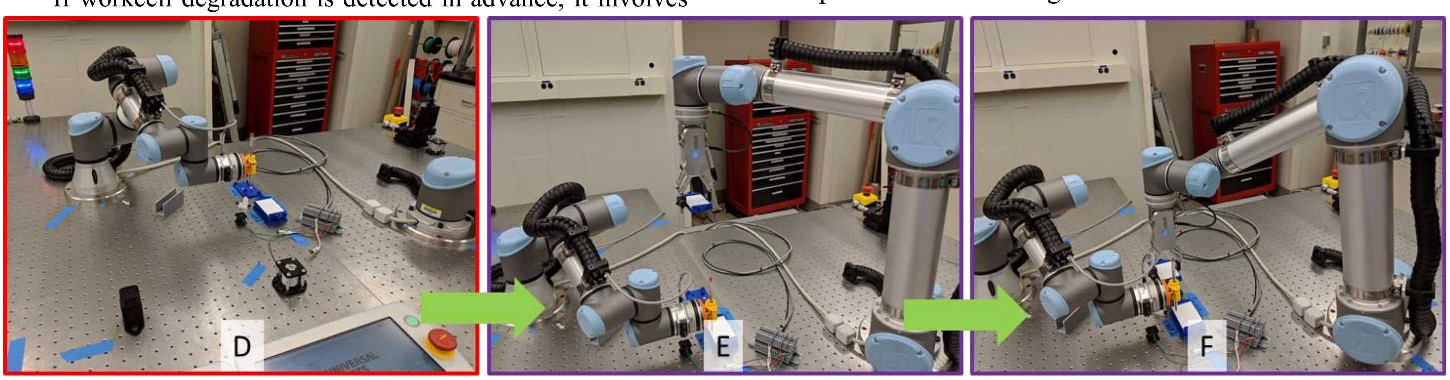

Figure 3. UR3 APPROACHING PART 01 ON FIXTURE 1 (D), UR3 DRAWING ON PART 01 AND UR5 MOVING PART 02 TO FIXTURE 2 (E), UR5 PLACING PART 02 ON FIXTURE 2 (F)

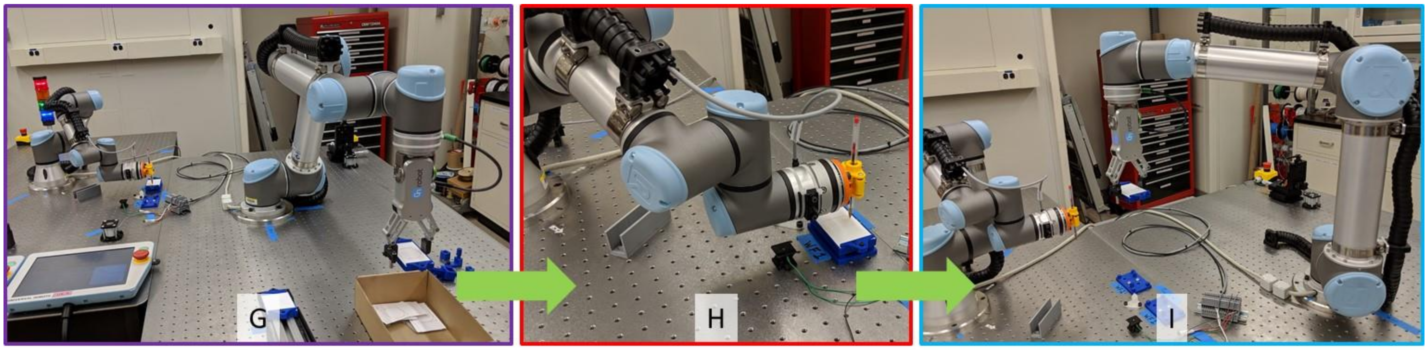

Figure 4. UR5 MOVING COMPLETED PART 01 TO OUTPUT BIN (G), UR3 DRAWING ON PART 02 IN FIXTURE 2 (H), UR5 MOVING PART 02 FROM FIXTURE 2 TO THE OUTPUT BIN (I)

they have deviated from their baseline specification. This research includes the development of a low-cost, innovative sensor that supports a minimally-invasive testing process which can be executed before or after the workcell's manufacturing operations with minimal impact to the cell's productivity. There is a high probability of success for this effort given that the test method's constituent sensor can be replicated at minimal cost and flexibly deployed within a target workcell. This approach is discussed in greater detail in the Current Efforts subsection in this paper.

- *Who cares?*

  Anyone in the manufacturing industry that manufactures robots, integrates robots into manufacturing operations, or uses robots in their factory will care about this effort. These stakeholders can all benefit from the successful development and dissemination of this effort. These groups should care about this work because process and equipment downtime due to maintenance, especially unplanned downtime due to faults or failures, can be a substantial cost to an organization.

- *What impact will success have? How will it be measured?*

  The successful execution and dissemination of this work is expected to have tremendous impact on the manufacturing community. The manufacturing community will gain a reliable and consistent method that they can integrate into many of their robot workcell operations including those that feature robots performing material handling or path planning operations. Technology integrators will gain a test method that they can build into the robot workcells that they supply their customers. Likewise, robot manufacturers will have a greater awareness of how their products are tested in-situ which may drive them to build the robot-based test method components into their robots while the robots are being fabricated. Measuring this impact will include capturing the number of manufacturers that integrate this method into their robot-based workcells and the number of active robot workcells that incorporate this method. Similarly, the number of integrators that choose to offer this test method as a PHM option and the number of workcells they output with this method will be captured.

Research Plan and Status

This research plan follows the path of:

1. Conduct case studies – Completed with the generation of a comprehensive workshop report identifying numerous roadmap action plans of key measurement science challenges in the PHM field [10]. Action plans described in this report that motivate the robot workcell research include: Advanced Sensors for PHM in Smart Manufacturing, Identification of PHM Performance Metrics, and Failure Data for Prognostics and Diagnostics.

2. Identify an appropriate use case(s) – Completed with the determination of the two-robot workcell use case. This configuration can also be considered an abstraction of a robot and machine tool workcell [8, 14]. Part of this effort has also included identifying the different degradation modes of the workcell [7].

3. Identify critical performance metrics – In Process. This has begun with determining that the workcell's kinematic chain will be monitored regarding its influence on the accuracy of the robot's TCP and the accuracy of the part's movement within environment [7]. Similarly, process-level metrics

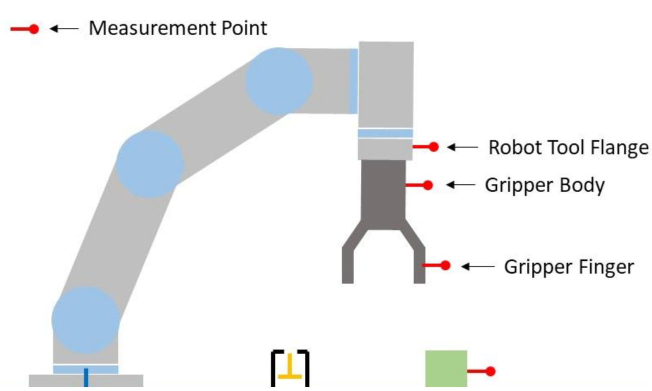

Figure 5. VISUAL REPRESENTATION OF TEST POINTS ALONG THE KINEMATIC CHAIN OF THE ROBOT AND OTHER WORKCELL ELEMENTS

have been identified that that can inform about the workcell's productivity during operation of the use case [15]. Additional metrics are still being explored for inclusion.

4. Develop test methods – In Process. A test method that monitors the health of the kinematic chain at various points [along the chain] has been developed [7]. Figure 5 presents a visual representation of multiple test points along the kinematic chain of the robot, the gripper, and the part that can all uniquely influence part and process quality. The test method is being verified at NIST. Likewise, technology integrators and manufacturers are being engaged to validate the implementation within actual manufacturing operations. The verification and validation efforts will be discussed further in the Current Efforts section.

5. Capture reference dataset(s) – In Process. This will be discussed in detail in the Current Efforts section.

6. Contribute technical basis to the standards community – Not yet started. Test method verification and validation must occur prior to this research being introduced into the standards community. In support of the NIST's PHM research efforts, NIST personnel have been a driving force in the creation of a newly formed American Society of Mechanical Engineers (ASME) subcommittee on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations [33]. The vision is that the technical basis of the robot workcell research will be integrated into guideline documents developed by this subcommittee when the research has sufficiently matured.

Data Collection, Verification, and Validation

Current efforts are focused on capturing reference datasets within the representative manufacturing workcell, verification of the novel sensor that has been developed to detect degradation in the kinematic chain, and validation of the kinematic chain test method within industry.

The kinematic chain test method and the corresponding discrete positioning sensor have been developed at NIST. As discussed in [7], this test method relies upon the inspection of the workcell's kinematic chain to identify and track degradation of workcell elements. This is accomplished by measuring the positioning repeatability of critical points (shown in Figure 5) along the kinematic chain. The test method is paired with a custom-built sensor that indicates discrete measurements of whether an element along the kinematic chain is maintaining its accuracy and therefore, repeatability. This technology is described as a "Position Verification Sensor with Discrete Output" (U.S. Provisional patent application serial number 62/732,059) and is shown in Figure 6. The overall test method can be executed with other sensing technology; the development of this new sensor was motivated by providing the community with a relatively low-cost solution that can be mass produced and readily integrated within many existing workcells. The expectation is that the sensor will be produced at a cost of between $50 to $100 USD (less if mass-produced). The sensor and corresponding test approach are likely to be an economical alternative to reactive maintenance. Capturing data from the sensor at specific time horizons or before/after certain activities can influence scheduling of maintenance activities in an effort to minimize workcell downtime and maintenance costs.

The sensor provides feedback when a cylindrical pin is vertically inserted into the top of the sensor within the manufactured tolerances such that only the inner button (shown within the green inner circle in Figure 6) is depressed, and the outer surface (shown within the red outer surface perimeter circle in Figure 6) is not touched. The implementation of the kinematic chain test method calls for one or more sensors to be placed within the work volume of the robot(s) within the workcell. The kinematic chain test method is engaged after a specified amount of production cycles or is directly forced by the operator through the PLC during certain windows (e.g., at the start of a shift, at the conclusion of the work day, or as part of preventive/routine maintenance). Two sensors are currently deployed in NIST's representative manufacturing workcell – an early prototype that is within the reach of the UR3, and the current prototype (shown in Figure 6) that is within the reach of the UR5.

For the NIST use case, test method execution begins with the UR3 moving its pen tip and attempting to press the inner button of the sensor within its reach. Next, the UR3 tests attempts to insert the pin (attached just above its tool flange) into the sensor. Success or failure is noted. The kinematic chain of the UR5 is then tested. This subprocess begins with testing the robot arm. This is shown in both Figure 7A and Figure 7B. After the robot arm is tested, the gripper body is tested, and the gripper fingers (while open) are tested. These activities are shown in Figure 7C and Figure 7D. Next, the gripper fingers (while closed) are tested. Lastly, the robot picks up a test part, that contains a vertical pin, and manipulates the test part with the sensor to yield a pass or fail result. The results of this test method produce a combination of pass and/or fail results regarding the

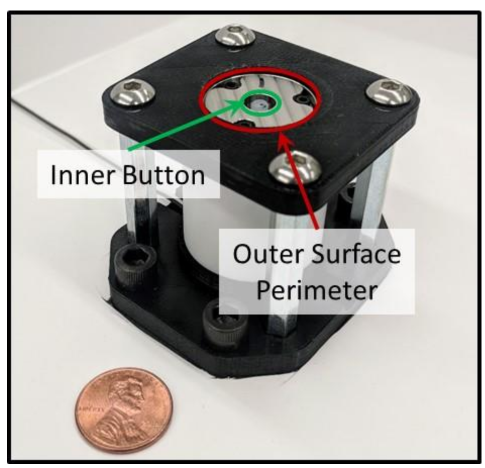

Figure 6. "POSITION VERIFICATION SENSOR WITH DISCRETE OUTPUT" – U.S. PROVISIONAL PATENT APPLICATION SERIAL NUMBER 62/732,059

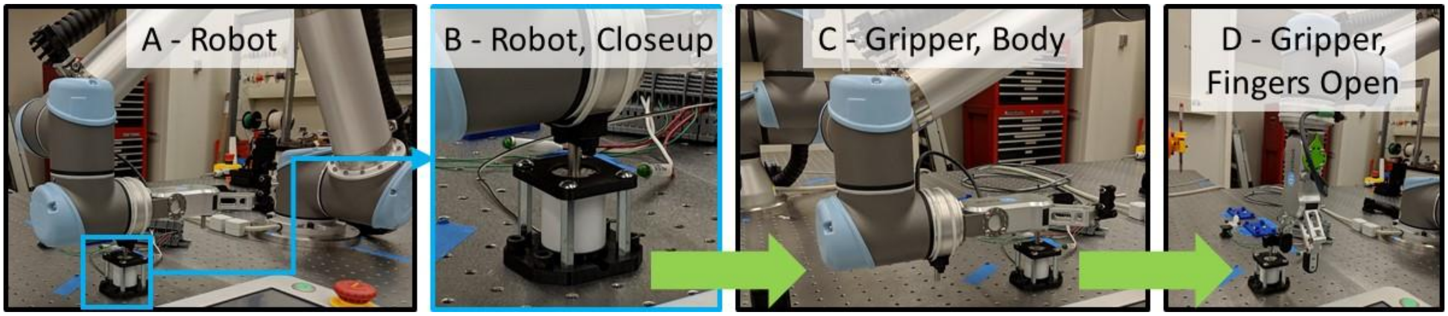

Figure 7. SUBSET OF TEST POINTS OF THE KINEMATIC TEST METHODOLOGY APPLIED TO THE NIST UR5

elements that were tested. Analysis of the results can highlight which, if any, of the elements in the kinematic chain are out of the tested specification. This information can be used to further troubleshoot specific elements of the workcell, perform maintenance on one or more elements or recalibrate an element of the workcell until the necessary maintenance can be performed. Feedback from this test method can also be correlated with process level and robot controller data to further isolate sources of degradation.

There is value to both NIST researchers and the manufacturing community in capturing reference datasets and making them publicly available. Reference datasets afford NIST the opportunity to develop, verify, and validate its methods and tools on representative manufacturing data from its robot workcell. Data captured in this environment presents realistic variation similar to data collected from an actual manufacturing facility. The manufacturing community benefits from accessing these NIST reference datasets since these datasets are freely available (i.e., no cost), will be annotated, contain more context than is typical for data captured in real manufacturing operations, provide data to support innovative technology development, and offer objective data to promote independent technology assessments. A series of data collections are planned with the first data collection being complete. These specific collections are driven by the need to capture a baseline of health and performance under several reasonable operating scenarios; followed by collections under various degradation conditions (either real or simulated). The steps in the series are:

- Baseline operation with plastic parts (28 g per part), no simulated degradation modes, all part geometrics are within tolerances, fixture geometry is within tolerances, gripper fingers are within tolerances. 60 parts are run.
- Baseline operation with **heavier parts (>> 28 g)** (e.g., steel or aluminum – exact mass is to be determined), no simulated degradation modes, all part geometrics are within tolerances, fixture geometry is within tolerances, gripper fingers are within tolerances.
- Operation with plastic parts, **with simulated backlash** (i.e., backlash can be simulated at each of the six joints of each robot arm. The exact joint(s) and robots that will present the backlash are still to be determined), all part geometrics are within tolerances, fixture geometry is within tolerances, gripper fingers are within tolerances.
- Operation with plastic parts, **with simulated slip** (i.e., slip can be simulated at each of the six joints of each robot arm. The exact joint(s) and robots that will present the slip are still to be determined), all part geometrics are within tolerances, fixture geometry is within tolerances, gripper fingers are within tolerances.
- Operation with plastic parts, no simulated degradation modes, **part degradation with respect to its interface on the fixture** (the number of parts to be degraded in the experiment is still to be determined), fixture geometry is within tolerances, gripper fingers are within tolerances.
- Operation with plastic parts, no simulated degradation modes, all part geometrics are within tolerances, **fixture geometry is degraded with respect to its interface with parts, gripper fingers are within tolerances**.
- Operation with plastic parts, no simulated degradation modes, all part geometrics are within tolerances, fixture geometry is within tolerances, **geometry of gripper fingers where they contact the part is degraded** (exact degradation and if it will occur on one or both fingers are still to be determined).
- Operation with a **combination of degradations**

The first dataset was captured from the workcell during the representative manufacturing operation where 60 parts were 'processed.' This involved six unique business card holders, numbered 1 – 6, being cycled through the workcell with blank business cards justified to the bottom left of the holder. Prior to the execution of the 60 runs, the robots cycled through the motions of processing 30 parts, yet no parts were fed to the robot during this time (this was done as a purposeful warmup). The input tray was loaded with an initial three parts (i.e., business card holders 1 through 3) shown in Figure 2B. PLC data monitoring and collection was turned on for process data and robot controller-level data for both the UR3 and UR5. Robot data was also directly captured from the robots (in addition to being captured through the PLC). The reason robot data is captured from two separate sources is because capturing it directly from the robots' controllers provides high resolution data; capturing lower resolution robot controller data through the PLC adds a greater measure of assurance regarding time synchronization between the process and robot controller data feeds since the PLC time is captured in all data files. Additionally, data is collected from the OptoForce Force/Torque sensor that is mounted between the tool flange and pen holder on the UR3. The 60 runs were completed in approximately 48 minutes. Besides capturing the noted data files, the robot script files, configuration files, and log files were captured from the UR3 and UR5 in case any operational faults were discovered while reviewing the data.

Presently, the dataset is under examination where the conclusions will be presented in a future article. Likewise, the lessons learned from this dataset will inform on the expected next data collection that will feature increasing the weight of the parts.

In parallel with capturing reference datasets on the workcell's operations under varying conditions, it is important to verify the discrete sensor. To date, manual verification of the sensor has been done using a hand-driven 3DOF linear stage (shown in Figure 8). Automated verification is planned with motorized drives that will increase the efficiency of this activity and test in a random pattern (as opposed to the very deterministic pattern used during manual verification).

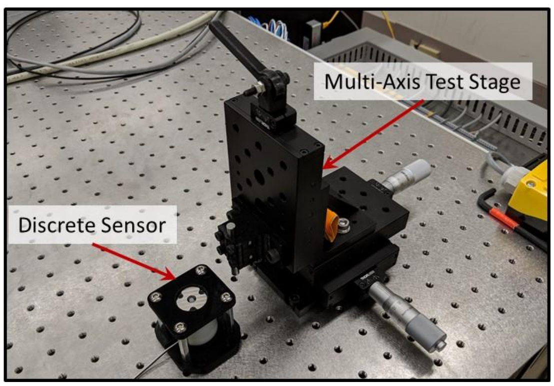

Figure 8. DISCRETE SENSOR AND TEST STAGE

The other active effort focuses on the validation of the kinematic chain test method. This involves the determination of the appropriateness of the test method within relevant manufacturing environments. Collaborations are being explored with external partners including a robotics distributor, technology integrators, and manufacturers. The expectation is that the kinematic chain test method will be piloted in a manufacturing environment or integrated into a developmental cell.

Integrating one or more developmental sensors in a functional manufacturing workcell along with executing the test method should offer valuable feedback to NIST researchers on the validity of the test method, the performance metrics being captured, and the viability of the sensor. Likewise, manufacturers will have the opportunity to discover the presence of any health degradations across their robot's kinematic chain and determine where, along the kinematic chain, degradations are present. Given the developmental status of the sensor, the sensor has yet to be ruggedized for extensive use in an actual environment. The expectation is that the sensor's deployment will be limited to relatively clean workcells (e.g., workcells with minimal to no usage of fluids or lubricants, and workcells that do not output metal chips).

FUTURE WORK AND CONCLUSIONS

A strong foundation is established to conduct research in developing the appropriate measurement science to verify and validate robot workcell PHM technology. The manufacturing community has a need for independently-developed test methods, reference datasets, and guidelines to assess and advance the state of the art in monitoring, diagnostic, and prognostic technologies for manufacturing robot workcells. To date, case studies have shown a need for the measurement science, a use case has been articulated, and a test bed has been constructed. Performance metrics have been identified and a test method has been produced which are both still being iterated upon. More recently, a reference dataset has been captured with additional datasets being planned; manual verification of the sensor has been completed with a more comprehensive automated verification being planned; and validation of the test method and sensor are being explored. As the workcell-level test methods mature, the feedback from these test methods will feed into the robotic-level testing which heavily factors in the robot's kinematic model and aims to identify specific joint errors. Another intersection of the robot-level and workcell-level effort will be that of simulating slip and backlash of specific joints at the robot level (this is already mentioned in the workcell-level research and is expected to be done concurrently at the robot-level). Ultimately, this measurement science will be transitioned into standards or guidelines to further disseminate this work and promote best practices of assessing robot workcell health.

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NIST DISCLAIMER

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