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# Quick health assessment for industrial robot health degradation and the supporting advanced sensing development

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Keywords: Robot health assessment Industry robot Robot accuracy degradation Advanced sensing PHM	Robotic technologies are becoming more integrated with complex manufacturing environments. The addition of greater complexity leads to more sources of faults and failures that impact a robot system's reliability. Industrial robot health degradation needs to be assessed and monitored to minimize unexpected shutdowns, improve maintenance techniques, and optimize control strategies. A quick health assessment methodology is developed at the U.S. National Institute of Standards and Technology (NIST) to quickly assess a robot's tool center position and orientation accuracy degradation. An advanced sensing development approach to support the quick health assessment methodology is also presented in this paper. The advanced sensing development approach includes a seven-dimensional (7-D) measurement instrument (time, X, Y, Z, roll, pitch, and yaw) and a smart target to facilitate the quick measurement of a robot's tool center accuracy.

### 1. Introduction

Advanced technologies are emerging in manufacturing, especially in the domain of cutting-edge information and communication technology, to improve manufacturing competitiveness and efficiency. Smart Manufacturing, which is the fourth revolution in the manufacturing industry, presents a fully-integrated and collaborative manufacturing system that responds in real time to meet the changing demands and conditions within factories and supply networks [1,2]. The successful implementation of smart manufacturing will bridge and connect hardware, software, and data to increase operational efficiency, asset availability, and improve quality while decreasing unscheduled downtime and scrap [3-6]. As smart manufacturing evolves, industrial robots are filling the need for advanced solutions in many manufacturing environments including automotive [7-9], electronics [10,11], consumer packaged goods [12], and aerospace manufacturing [13-15]. Smart Manufacturing is having a positive impact on factory floor-level robotic operations. More diverse systems, sub-systems, and components are being connected to increase the robot work cell capabilities. However, more complexity can lead to more sources of faults and failures. A robot system's health degradation, including robot tool center position (TCP) accuracy degradation, can compromise the efficiency, quality, and productivity of a manufacturing system. It is important that the robot system's health degradations are understood so that maintenance and control strategies can be adjusted to compensate for these degradations.

An industrial robot system is defined to include a robot, end-effector (s), and any equipment, devices, or sensors required for the robot to perform its tasks [16]. Many possible faults and failures could occur within the robot system given this system complexity. Faults and failures can be divided into three principal categories [17-19]: faults, soft failures. and hard failures. A fault is defined as a defect that is an inherent weakness of the design or implementation. For example, a fault could be an incorrect signal value or an incorrect decision within the system. A fault may result in a system's degradation [20]. A soft failure is defined as a condition when the system performance starts to degrade, where 'wear and tear' and/or external changes have occurred that have compromised the baseline health of the system. Under a soft failure, the manufacturing process is not capable of meeting its performance specifications [21]. If the performance degradation worsens, quality can decrease below specifications indicating a defect or unacceptable result. A hard failure is defined as a condition when a component or a piece of equipment breaks, or a system or component is unable to function as required [20]. In the hard failure condition, the manufacturing process is typically either frozen or shut down.

Faults and failures can impact a robot system in numerous ways, including influencing some key performance factors of a robot, e.g., accuracy, velocity, force, and torque. These factors are commonly identified as critical indicators of the system health. Robots are employed to move and manipulate end-effectors accurately (e.g., grippers, welding wands) to certain specifications. Tool center accuracy can be used to assess the health of an industrial robot. For example, accuracy is

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Received 16 December 2017; Received in revised form 2 April 2018; Accepted 9 April 2018 0278-6125/ © 2018 Published by Elsevier Ltd on behalf of The Society of Manufacturing Engineers. a critical health factor for applications that demand both position and path accuracy (e.g., arc welding, robot machining, and robot composite material layout). If accuracy degrades, a robot will weld or drill at incorrect positions. The production quality will be compromised. Accuracy is also critical for applications that are using an external system to position parts relative to the robot arm, or using an external system to guide a robot's operation. For example, a vision system may be used to locate a part; this information would be passed to the robot controller that would then command the robot to pick it up [22]. The degradation of a robot's position and orientation accuracy will lead to a decrease in manufacturing quality and production efficiency. Given the high output rate of production lines, it is important to develop techniques to assess a robot system's health conditions that predict soft and hard failures. Robot health degradations are less observable compared to system freezes or shutdowns. In the robot health degradation condition, the robot is still running and appears to be making parts, but actually working at a decreased level of performance and/or quality.

As a subset of the NIST's Prognostics, Health Management, and Control (PHMC) project, PHMC for robotics research is ongoing. The research aims to develop the measurement science within industrial robotics domains to promote the advancement of monitoring, diagnostic, prognostic, and maintenance strategies [23,24]. One output of this research involves developing a quick health assessment methodology emphasizing the identification of the robot accuracy changes. This methodology will enable manufacturers to quickly assess the robot's tool center position and orientation accuracy degradation.

Section 2 in this paper will give an overall view of the quick health assessment methodology. Details of the modeling and algorithm for the methodology are presented in previous publications (refer to [25,26]). Section 3 will present the development of the vision-based 7-D measurement system. Section 4 will present the innovative design of the smart target. Section 5 wraps up the paper and highlights future work.

#### 2. Workflow of the quick health assessment methodology

A quick health assessment is a methodology that aims to assess the robot tool center accuracy degradation throughout the robot work volume. The methodology includes: 1) advanced sensing to measure the robot tool center positions and orientations; 2) a test method to predefine the robot movements and model the robot errors to reflect the robot geometric and non-geometric errors; and 3) algorithms to process measured data to get the robot health assessment using limited measurements. The quick health assessment methodology addresses the following challenges:

1) Measuring the actual robot positions and orientations with the minimum interruption of production. The details of the challenges and solutions for the advanced sensing development will be presented in Section 3 and 4 of this paper.

- 2) Assessing the robot tool center errors from all directions. As shown in Fig. 1(a), a robot could have multiple inverse kinematic solutions to reach to a three-dimensional position in Cartesian space. As a result, the error magnitude and direction can change by choosing different inverse kinematic solutions. This makes the assessment of the tool center accuracy difficult since it's hard to measure the accuracy from all directions.
- 3) Assessing the accuracy of the whole robot work volume using limited measurements. A robot may work on different tasks within its work volume using different poses. As shown in Fig. 1(b), the spherical space is the work volume calculated for this robot. The inner layer represents the work volume calculated for the robot tool center. The outer layer of the spherical space represents the work volume calculated for the assessment methodology should assess the robot's accuracy degradation over the whole work volume with all possibilities of different poses of the arm. It's impossible to take unlimited measurements since the interruption of production is expensive. An efficient test method is needed to assess the robot's overall health using limited measurements.
- 4) Decoupling the measurement instruments' uncertainty from the actual robot errors: The uncertainties coming from measurement instruments are usually treated as joint errors [27]. In this case, the assessment results may be biased. The modeling and algorithm development are needed to solve these challenges.

The goal of the methodology is to enable manufacturers to assess a robot's tool center accuracy degradation quickly. The quick health assessment can quickly detect problems if the of environmental conditions change, reconfigurations occur in the work cell, or manufacturers need to make sure the robot has not experienced a degradation when an important part is put in the work cell. The use of this methodology will monitor the degradation of robot performance, reduce unexpected shutdowns, and help the optimization of maintenance strategy to improve productivity.

The workflow of the quick health assessment development is shown in Fig. 2. The workflow contains the development of advanced sensing used to take measurements (will be presented in Section 3 and 4), a test method, algorithms for data processing and health assessments, the root cause analysis, and PHMC remedy techniques.

To address the second and the third challenges previously listed, a test method with a fixed loop motion was developed. An important feature of the test method is that it requires the robot movements to be evenly distributed in both joint space and Cartesian space. The even distribution in joint space prevents missing errors or adding too heavy weights on errors. The even distribution in Cartesian spaces enables the evaluation of the arm accuracy and rigidity throughout the robot working volume. A fixed loop motion is designed to satisfy those requirements. In the meantime, collision avoidance of the robot arm with



Fig. 1. Robot working volume and multiple inverse kinematic solutions in Cartesian space.



Fig. 2. Workflow of the quick health assessment methodology.

obstacles and with the robot structure itself is also performed (the details of creating a fixed loop motion are presented in the papers [25,26]). The fixed loop motion for the test method will be executed periodically and in a relatively short amount of time (10–15 min). While the robot tool center is moving to these pre-determined positions, X, Y, Z, roll, pitch, yaw, and time (7-D information) data are being captured from the 7-D measurement system developed at NIST (as shown in the top block of Fig. 2). All measurements will be taken under a global coordinate system which is defined on the 7-D measurement system. Measurement data is inputted into the test method model.

Traditional modeling methods for robot errors assume that robot joint motion is ideal, and the geometric relationships between the joints are constant [27]. Yet there exist non-geometric errors, such as the nonideal motion of joints, and deflections of the structure and joints due to external loading, gravity, backlash, etc. These errors are not constant values. They are position dependent errors. The error model built for the quick health assessment test method is different from the traditional error model. Parameters that describe the geometric relationships are not constant values, but are functions of the axis locations. This means the error model can model not only the position-independent geometry errors, but also the position-dependent motion errors. An example of a robot's serial kinematic structure with coordinate frames is shown in Journal of Manufacturing Systems xxx (xxxx) xxx-xxx

Fig. 3. The real axis has deviated from its designed position. The errors of this axis are represented as: (1)  $\delta_x$  - radial error motion of i-axis in the X direction; (2)  $\delta_v$  - radial error motion of i-axis in the Y direction; (3)  $\delta_z$ - axial error motion of i-axis in the Z direction; (4)  $\varepsilon_x$  - tilt error motion around X of i-axis; (5)  $\varepsilon_v$  - tilt error motion around Y of i-axis; and (6)  $\varepsilon_z$ - angular positioning error (also called scale error of the rotation axis). The error model of the joint is described in the equation in Fig. 3. The  $\delta(\theta)$  and  $\epsilon(\theta)$  are not constant values. They are functions of axis locations which we refer to as a higher order model (compared to the zero order model) [28], which means the model can handle non-geometric errors, such as the non-ideal motion of joints and deflections of the structure and joints. Also, to decouple the measurement instruments' uncertainty from the actual robot errors, an implicit loop method is implemented. In the implicit loop method, a closed loop is formed from the first link out to the tool tip, and then back to the first link via a measuring device. The displacements around a closed loop sum to zero (or Identity matrix). With this convention, the measurement instrument's uncertainty is modeled inside the model equation using a weight. Joint and end-effector measurements are equally weighted, with weights assigned according to the accuracy of each joint. There are two outputs from data analysis. The first one is the derived errors from the calculation of the robot tool center accuracy of the robot through the work volume. The advantage of this method is that the uncertainties of the measurements are decoupled from the true errors and won't bias the analysis result. The second output is to find the maximum likelihood estimation of parameters to minimize the error function. This result can be used to detect the root cause of axis errors. Moreover, compensation can be calculated to improve the accuracy of the kinematic model, which can be used in the future root cause analysis and PHMC remedy development as shown in the two bottom blocks in Fig. 2.

The advanced sensing development is an important part of the quick health assessment methodology. The time and the 6-D information (X, Y, Z, roll, pitch, and yaw) are needed to describe the robot tool center accuracy. Sections 3 and 4 of this paper will focus on advanced sensing to measure the robot's tool center position and orientation.

## 3. Advanced sensing development to support the quick health assessment methodology

The advanced sensing developed at NIST provides the time and the 6-D information as the inputs to support the quick health assessment methodology. The integrated 6-D sensor is needed. The reason to avoid using multiple lower dimensional sensors (e.g., using one-dimensional sensor or two-dimensional sensors) is that the setup is complex and introduces error stacking.



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The advanced sensing development includes the development of the measurement instrument and a special target. Existing measurement instruments that can measure either 3-D (three dimensional - x, y, and z) or 6-D information are shown in Fig. 4. The outputs of the instruments are actually defined by what targets are used. If 3-D targets are used, measurement instruments can measure 3-D information. If 6-D targets are used, the measurement instruments output 6-D information.

Instruments in Fig. 4 use different principles to take measurements, including laser-based (laser trackers), time-of-flight (laser radars), and vision-based (optical trackers) technologies. In Fig. 4, the number one through number three measurement instruments are laser trackers from different manufacturers. Laser trackers are instruments that can measure 3-D coordinates by tracking a laser beam to a spherically-mounted retroreflector (SMR) target (as shown in the top left 3-D target picture of Fig. 4). Since measurements need to be taken by holding an SMR in contact with the object of interest [29], laser trackers are contact measurement instruments. A laser tracker contains a laser beam and two angular encoders. The laser beam is used to measure the distance from the laser tracker to the SMR. Encoders measure the angular orientation of the tracker's two mechanical axes: the azimuth axis and the elevation axis. The angles from the encoders and the distance from the laser are sufficient to precisely calculate the center (x, y, z) of the retroreflective targets. For laser-based instruments, one laser beam can track only one SMR target at a time. Sometimes multiple SMRs are used to represent a coordinate frame. In this condition, laser-based instruments need to measure the SMR targets one by one. Because the beam switching and re-lock on different targets take time, the SMRs and the object of interest need to stay stationary during the measurement process. Using multiple SMRs and laser-based instruments to measure 6-D information cannot be applied to dynamic measurements, such as measuring the movements of a robot arm. As a result, it cannot satisfy the measurement requirements of the robot quick health assessment methodology. To increase measurement speed and efficiency, special 6-

D targets are designed for laser trackers to capture the extra orientation information as shown in the picture of the 6-D targets in Fig. 4. The extra orientation information is measured by embedding other sensors in the target or adding a camera system on the tracking head to capture the features that define the coordinate frame. For example, in the bottom left picture in Fig. 4., the 6-D target uses an SMR and multiple light-emitting diodes (LEDs) to define a coordinate frame. However, since the laser beam still needs to lock on the SMR(s) on the 6-D target, laser-based instruments require the maintenance of line-of-sight between the laser tracker and the target. This means that the tracker will ultimately lose its view of the target when observing the target on a robot rotating to an angle. In this case, the robot's rotation has to be limited, which is not suitable for the quick health assessment methodology. For the quick health assessment methodology, the robot tool center needs to be measured in different positions and orientations throughout the robot's work volume.

The fourth measurement instrument in Fig. 4 is a laser radar. This is a typical scanning instrument (using the time of flight technologies typically) [29]. Laser radar scans parts and outputs measurement data as 3-D point clouds. Laser radar can measure a 6-D target (e.g., with multiple reflective spheres that define a coordinate frame as shown in Fig. 4). However, getting the 6-D information from point clouds may take multiple steps in software operations. The first step is to segment the 6-D target's point cloud from the surrounding objects. Then outliers need to be removed. After that, best-fit is performed to fit a sphere. The last step is to extract the sphere center from the fitted sphere. The bestfit accuracy varies depending on the quality of the point cloud and the quality of segmentation. Laser radar is expensive and not an efficient measurement system for the robot 6-D information collection.

The fifth measurement instrument in Fig. 4 is an example of optical trackers. Optical trackers are vision-based instruments, using two or more cameras. Each camera is equipped with an infrared (IR) pass filter in front of the lens. A ring of IR LEDs is mounted around the lens to



Fig. 5. 7-D measurement system.

illuminate IR light to the measurement space periodically. Objects that need to be tracked are equipped with retro-reflective markers (e.g., reflective spheres). The 3-D position can be measured by using a single marker in the measurement space. Multiple markers can be used to define a coordinate frame. For example, the 6-D target at the bottom right in Fig. 4 has large mechanical fixtures holding 2-D markers to define a coordinate frame. The large mechanical fixture may interfere with the robot's end effector tools. The shortcoming of the IR visionbased measurement instrument is that the images of the infrared cameras only contain the markers. They cannot see the measurement objects or the environment. When ambient lights exist in the environment, the reflected lights from ambient objects or targets will be treated as real targets. There is no redundancy when applications are used under a complex industrial environment [30].

To avoid the limitations of the existing measurement instruments and address the challenges of advanced sensing requirements to support the quick health assessment, a 7-D measurement system was developed at NIST as shown in Fig. 5. The measurement system consists of a vision based measurement instrument and a target. Outputs from the 7-D measurement system are time, X, Y, Z, pitch, yaw, and roll information under the fixed instrument coordinate system. The 7-D measurement system is designed and embedded with a time synchronization feature.



Fig. 6. Three-point method to define a coordinate frame.

Time synchronization is important for the analysis when fusing this data with other sensor data for deep robot system health analysis. The 7-D measurement instrument uses two high-speed color cameras. The reasons to use a vision-based design are because: (1) A vision-based system can measure position and orientation information simultaneously; (2) Novel camera technologies enable the achievement of camera sub-pixel accuracy. The sub-pixel accuracy converts to the measurement system's high degree of accuracy after optical triangulations; and (3) Since camera technology has become mature, a visionbased system is relatively cost-effective to integrate [31]. The 7-D measurement system doesn't use infrared cameras, but rather highspeed color cameras. Redundant information from color images and advanced color image processing technologies are utilized to get more accurate target detection results. A high-performance computer will be used to perform the image processing. A special target was designed to work with the measurement instrument to measure the robot position and orientation information. Software tools were developed to perform the measurements. As shown in Fig. 5, the 7-D measurement instrument is mounted on the floor or table, which is at the opposite end of the kinematic chain from the target. The smart target is mounted on the last link of the robot arm. No alignment is needed from the 7-D measurement instrument to the smart target so that the 7-D measurement instrument can be moved to other robots/stations without the need for time-consuming alignment procedures.

For the vision-based system, three major technologies determine the accuracy of the measurement instrument. These technologies include the distortion correction for camera sensors and lenses, instrument calibration of the two camera relationships, and the accurate feature detection of targets. Since the measurement volume of the 7-D measurement instrument is large (needs to cover a robot's work volume), an advanced image distortion correction algorithm is developed for the camera sensor distortion. The algorithm uses a checkerboard plus a "3-D rig" technology. An initial camera distortion model is built utilizing the checkerboard. Then the distortion parameters are optimized using known positions in a large 3-D volume. To verify the distortion correction results, multiple line features are printed on an adhesive sheet and put on top of a precision flat plate (the flatness of the plate is 20 µm). Cameras take images of the lines from different angles and distances. Algorithms for line center detection with sub-pixel accuracy are developed to get the straightness errors of the fitted line. Results are compared with and without image correction. For the two camera relationships calibration, the common set of checkerboard images and the 3-D rig data (taken by both cameras) can be used to calibrate the relative positions and orientations of the two cameras. Additionally, a self-calibration method is created by utilizing the features (e.g., size and angle features) in the smart target to self-calibrate the cameras with respect to one another when the system is used on site. For the accurate feature detection of targets, an innovative smart target is designed which will be detailed in the next section. High-frequency differential technology is also used to subtract background noises to improve accuracy. Parallel calculation and hardware acceleration are used for fast image processing. Graphical processing unit (GPU) programming is utilized to enable the implementation of complex image processing algorithms. The innovative target design is described in the next section.

#### 4. An innovative target - smart target development

Innovative target design is an important part of this measurement system development. To measure a robot tool center's x, y, z, yaw, pitch, and roll information allows one to measure the tool center's coordinate frame. A coordinate frame has an origin that defines the position x, y, and z information. The axes define the yaw, pitch, and roll angle information. To design a 6-D target, the target needs to contain component features that are used to define/build a coordinate frame. The component features must be measurable by the measurement instrument.

A frame has four basic components: an origin, a primary axis, a secondary axis, and a tertiary axis. A frame can usually be constructed by defining an origin and two of the axes. The third axis is naturally defined as an axis that is perpendicular to both other two axes. The origin is a point feature. The axes are vector features that contain a position and a direction. The most traditional way to define a coordinate frame is the three-point method, which is widely used by many vision-based measurement instruments. In this method, three point features are needed. As the example shown in Fig. 6 illustrates, there are three points: P1, P2, and P3 (in Fig. 6(a)). The three points are used as origin, the point defining an axis (e.g., X-axis), and the point in a plane (e.g., XY plane). P1 is used to define the origin of the frame (as shown in Fig. 6(b)). P1 and P2 form a vector which represents the Xaxis. P1, P2, and P3 create the XY plane. The Y-axis is located in this XY plane, going through the origin, and perpendicular to the X-axis. The P3 point is not necessarily located on the Y-axis. It only indicates the Yaxis's positive direction.

Spherical targets (the top two pictures as shown in Fig. 7) are the most common artifacts used to define point features in Cartesian space.



Fig. 7. Spherical targets and 6-D targets using sphere artifacts.

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The roundness of the sphere target needs to be controlled so that the measurement of the sphere center will be the same when observed from different angles and views. The spherical targets can be used by different instruments from laser trackers, to radars, and to vision-based instruments. For point cloud generating instruments (e.g., scanning or radar measurement instruments), the surface of a spherical target is captured as a point cloud. Later the point cloud is best-fitted to a sphere. Then the center of the sphere is detected and used as a point feature. For vision-based systems, each camera captures a 2-D image of the spherical target from its view (a solid circle). The centroid of the solid circle is detected from each camera. Two (or more) cameras perform triangulation to construct a 3-D center of the spherical target.

Three or more spheres can be structured together to build a 6-D target that defines a coordinate frame (e.g., the structures of the bottom three pictures in Fig. 7). The reason for using more than three spheres is to provide redundant spheres when image blocking or overlapping occurs. The blocking/overlapping may come from different views of the target, or when the target rotates with the object of interest, the surrounding objects may block the view. An advantage of using traditional spherical artifacts and point features to define a 6-D target is that the algorithm is relatively simple (either circle center detection or best fit of a sphere). However, there are some challenges:

1) Sphere center detection accuracy and uncertainty: Using spherical artifacts and point features, the center of a sphere is the feature that needs to be captured by the measurement instrument. For point cloud measurement instruments, the sphere surface is captured as a point cloud. The best-fit method is utilized to detect the sphere center. If the point cloud can cover the whole range of the sphere as shown in Fig. 8(a), the sphere center detection can achieve good accuracies. That's why when using point cloud measurement instruments, users need to capture as much of the sphere surface as possible. In the real situation, only part of the surface will be captured as shown in Fig. 8(b). The best-fit result will be biased when one side of the surface data is missing as shown in Fig. 8(c). When using vision-based systems, a sphere target will project a 2-D solid circle on the camera sensor. The task is to detect the centroid of the solid circle. For the solid circle feature, image quality has significant influences on the accuracy of the centroid detection. Fig. 8(d-f) shows an example of the grayscale image. Fig. 8(d) shows the center part of the image is saturated. Under this condition, the camera exposure needs to be adjusted because a saturated image will lower the sensitivity of the center detection. The target center's small subpixel changes cannot be detected when saturated intensities cover up the grayscale changes. Fig. 8(e) shows the condition when



Fig. 8. Problem of sphere center detection accuracy and uncertainty.

the camera is out of focus. Fig. 8(f) shows the condition when a target is at a far distance and only a few pixels are highlighted on the camera sensor. These factors cause accuracy problems and create large uncertainties in locating the sphere center. Ambient light also has a strong effect on the sphere center detection accuracy and uncertainty.

- 2) Target size: The axis of a coordinate frame is defined using two points (two sphere centers) the origin and the point on the axis. If the two points are close to each other, a small position error of the point can cause a large deviation of the axis direction (or the angular error of the axis vector). Given the uncertainty of the point detection (from the sphere center detection), the larger distance between the two points, the smaller the angular error. So, the target size needs to be relatively large to have a bigger distance between the points. However, the target size cannot be too large because of the constraint of the mechanical target size. As a result, for this kind of target, angular measurement contains large uncertainties.
- 3) The technology used to stand out targets from the background: To simplify the target identification from a complex background, IR technology is utilized for existing optical tracking systems. Each camera is equipped with an IR pass filter in front of the lens, and a ring of IR LEDs around the lens to periodically illuminate the measurement space with IR light. Reflective spheres are used as markers. In this case, the optical tracker's image only contains the markers. They cannot see the measurement objects or the environment. When ambient lights exist, the reflected lights from ambient objects or targets will be treated as real targets [30]. Also, the accuracy of the reflective sphere needs to be considered. To make a sphere able to reflect IR light, either reflective material coating (expensive in manufacturing to guarantee coating accuracy) is applied, or reflective tapes are wrapped around a sphere. The wrapped spherical targets have challenges to control the roundness and can be used in some applications that require moderate accuracy specifications.
- 4) Lack of straightforward definition of a coordinate frame: When a multiple-sphere target is presented in front of the user, any sphere center can be used to define the origin or an axis. There is no unique or clear "definition" of a coordinate frame. When multiple coordinates exist in a system (e.g., multiple robots, machines in a smart manufacturing environment), it is difficult to understand the relationships of the instruments.

To address these challenges, NIST has developed an innovative smart target. The smart target is designed to be used by the 7-D measurement instrument, but also can be used by other types of measurement instruments. This smart target design is under consideration for a patent. The sketch of the smart target is shown in Fig. 9.

The smart target design uses line features to define the coordinate frame. The intersection of two line features forms the origin of the coordinate. The coordinate axes are formed as vectors passing through the origin and having the same normal directions defined by line features. As shown in Fig. 9, cylindrical light pipe artifacts are used to define the line features. The bottom picture in Fig. 9 shows an example white color light pipe (15 mm in diameter and 75 m m long). The light pipe can use different colors of LED illumination. In the smart target design, three colors of LEDs are used. Wavelengths are selected to match the narrow band filters on the 7-D measurement instrument's cameras to reduce ambient light effects. A specially finished light pipe surface creates the even light distribution along the cylindrical surface.

As shown in the Fig. 9 the top picture, two cylindrical light pipes intersect at the center of the smart target as a cross shape (or "T" shape). The origin of the smart target coordinate system is located at the intersection center of the two pipes. The two intersection light pipes are mounted on two or three mechanical rotation axes. Driven by sensors (e.g., level sensors) or weight balance, the cross pipes can constantly rotate toward the measurement instrument. This creates a



Fig. 9. Smart target.

non-blocking measurement of the target, even when the target is moving (e.g., the target is mounted on a robot, and the robot arm is moving). Moreover, the measurement uncertainty remains the same when the target rotates at different angles. On the edges of the smart target, light pipes with three different colors are used to define the x, y, and z axis directions. In Fig. 9, red light pipes define the X-axis direction, green light pipes define the Y-axis direction, and blue light pipes define the Z-axis direction. They are physically aligned perpendicular to each other. To provide redundancy of direction measurement from different views, multiple light pipes can be mounted in a parallel fashion on the smart target.

The bottom picture of Fig. 9 shows a camera image of the example white color light pipe. A center line feature is detected. The information of edge features, the parallelism of edges, points on the edge and center, and the inside intensity distribution are used for centerline detection. Compared with the traditional two-point method (two spherical centers in a close distance) to define a line direction, the cylindrical artifacts method creates high accuracy in line detection by utilizing more points and other supporting information. Also, the origin definition from the intersection of two line features (each 75 m m long) achieves higher accuracy compared with the traditional method of using a spherical center (usually 10 m m or 25 m m in size) to define the origin.

Electronic boards are placed inside the smart target body. The smart target is battery driven. The LEDs can be turned on/off using a remote control. The bottom plate of the smart target is the mounting plate that can be connected with different adaptors designed for different end effector tools. The 7-D measurement system needs to be designed such that its integration and use does not interfere with the robot system's normal operations. The adaptor is designed to avoid the scenario where a robot system's end-effector needs to be removed or adjusted to accommodate a target sensor. As an optional configuration, a small SMR target nest can be mounted at the intersection center to enable a laser tracker instrument to use the smart target. The smart target can be used as the common target to support the cross-platform systems to acquire 6-D information quickly and accurately.

In summary, the smart target designed at NIST has the following innovations:

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- 1) High accuracy that comes from the different design concept. Traditional targets used by vision systems are sphere features that define 1) the origin and 2) the direction of an axis. The uncertainties of the sphere center measurement are transferred one-to-one to the origin definition. The uncertainties are enlarged to axial direction definition since small distance errors can create large angular errors. By using the cylinder features, the axial direction is defined along the cylindrical target's center line. The constructed center line is more accurate by fitting with points along the 75 mm long light pipe, compared with the traditional method of using two close-distance points of two sphere centers. Also, extra features of the light pipe, such as the color, the edge features, etc., give more redundant information to improve the line detection accuracy. For the same reason, the origin that is defined by two-line intersection obtains higher accuracy compared with the traditional method of defining the origin using a sphere center.
- 2) Non-blocking measurement design to measure both static and dynamic TCP data. Traditional targets have the problem of bad pose (perpendicular to the camera) which is not sensitive to camera measurement, or the target may block itself in some poses. The smart target has the cross center mounted on rotary axes. The crosscylinder can always rotate toward the measurement system. This makes the smart target's origin good for measurement in different views without self-blocking. Multiple cylindrical light pipes on the smart target edges give redundancies for axis direction extractions in different views.
- 3) A unique definition of a coordinate frame. Traditional spherical targets don't have a unique definition of a frame. Any sphere can be used to define the origin or the axis. The 6-D smart target has a consistent and unique definition of a frame to avoid confusion when multiple coordinates exist in a system.
- 4) A hybrid target for the cross-platform measurement system. Other than supporting the robot quick health assessment, the smart target can be applied to broader applications with the need for 6-D information measurements. For example, the 6-D smart target can provide machine vision vendors with a new tool to detect 6-D information, or the smart target can help to register multiple instruments under a global coordinate. The smart target can be used as a common 6-D target for cross-platform measurement. In vision-based non-contact measurement systems, cylinder features are detected through vision sensors. The color information is used to speed the calculation and provide more redundant calculation in algorithms. In scanning-based non-contact measurement systems, cylinders can be constructed using point clouds captured by the measurement system. Center lines can be detected, and the cross center can be found. In contact measurement systems like laser trackers, cylinders can be measured by SMR probing. Center lines can be detected to form the two lines for axes direction. A laser target (SMR) nest can be mounted in the center of the cross to simplify the origin measurement.

The smart target supports the continuous measurement of the 6-D information of a moving object with high accuracy. The smart target can be applied to broader applications to acquire the object's 6-D information. The measured 6-D information can be used for many purposes besides the quick health assessment. It can also be used as the feedback control for motion, relative position/orientation monitoring of two items, and data registration for in-process inspection. These applications bring innovative ways to design smart functions in modern manufacturing systems.

#### 5. Conclusions

A quick health assessment methodology for industrial robot health degradation and the supporting advanced sensing development is presented in this paper. The novel features of the methodology include: 1)

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creation of innovative test methods to quickly assess the TCP accuracy degradation in a volumetric way; 2) capabilities to handle the robot geometric and non-geometric errors, and 3) capabilities to decouple the measurement instrument's uncertainty from the actual robot errors. The implementation of the quick health assessment can help to reduce unexpected downtime, improve productivity, efficiency, and quality, and optimize the maintenance strategy of the robot systems in smart manufacturing.

The advanced sensing was developed to enable the continuous measurement of the robot tool center 6-D information. The 7-D measurement instrument is designed with several features that differ from and exceed the performance of traditional stereo technologies, including a time synchronization feature that is designed for PHMC data alignment, advanced color sensor processing technology, and instrument calibration technology. The innovative smart target design is under consideration for a patent. The smart target can be used as the common target by cross-platform systems to acquire 6-D information quickly and accurately. The embedded line features enable the high accuracy definition of a coordinate frame to output the 6-D information. Future efforts are underway to measure the accuracy degradation during dynamic operations for applications that require high-precision motions. NIST is also seeking to develop additional industrial use cases.

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