# Sensors for Safe, Collaborative Robots in Smart Manufacturing

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***Abstract*—The U.S. National Institute of Standards and Technology (NIST) is developing performance metrics for collaborative robotic systems for smart manufacturing applications. Using a suite of sensor platforms, feedback mechanisms, and novel test artifacts, NIST seeks to provide industry with the means to characterize the performance of robots working collaboratively with humans and other robots. This report serves to outline the applications, requirements, and developmental opportunities for the sensors being used toward this effort. Sensing for safety, human-robot interaction, human-machine interfaces, and multi-robot coordination performance are discussed.**

**Keywords:** human-robot interaction, collaborative robots, robot safety, multi-robot coordination, human-robot interaction

## I. Introduction

The U.S. National Institute of Standards and Technology (NIST) is developing new measurement science for the assessment and assurance of the performance of manufacturing robotics by means of its Robotic Systems for Smart Manufacturing (RSSM) program [1]. One focus of the RSSM program is the evaluation of robot systems working with people and other robots [2]. The measurement science being produced includes test methods, metrics, and artifacts for the technology-agnostic verification and validation (V&V) of collaborative robots, their applications, and their behaviors.

For any form of collaboration to be possible, robots must be aware of their surroundings, including the people, tools, and equipment with which they are working. To support this, our work necessitates we must develop and employ novel sensing platforms and techniques to measure the performance of safe, collaborative human-robot interaction (HRI). These sensing platforms are integrated into the collaborative robot testbeds at NIST. The NIST testbeds consist of several collaborative robot platforms including:

- Five six degrees of freedom (6DoF) robotic arms,
- One 7DoF robotic arm,
- Two dual-arm 7DoF (14DoF total) robots, and
- Two mobile robot platforms.

The testbeds are complemented by a suite of sensor platforms used to monitor, measure, and provide feedback to these robots and their human operators. These sensors include multi-camera motion capture systems, stereoscopic cameras, commercial red-green-blue-depth (RGB-D) cameras, force/torque (F/T) transducers, and small-scale inertial measurement units (IMUs). These platforms are focused on the identification, localization, and tracking of humans, robots, and parts moving throughout a simulated flexible factory environment.

This paper outlines the sensor-enabled areas of research in collaborative robotics at NIST. Section II describes efforts in collaborative robot safety. Section III describes efforts using sensors integrated into the coordination and control of heterogeneous configurations of multiple robots. And Section IV discusses research on sensor-based, intuitive HRI. Throughout this paper, challenges and opportunities for continued sensor development are outlined, as are recommendations for standardized test methods for sensing V&V.

## II. Collaborative Robot Safety

In 2016, the International Organization of Standardization (ISO) published Technical Specification (TS) 15066, which outlines the safety requirements for collaborative industrial robot systems [3]. ISO/TS 15066 established four safety-related functions of collaborative robots, the two most notable being "speed and separation monitoring" (SSM; maintaining a safe separation distance between a human and an active robot), and "power and force limiting" (PFL; limiting the robot's transfer of pressures and forces onto the human body). Assuring the functionality of both is a challenge, primarily because ISO/TS 15066 currently lacks test methods for the V&V of these functions. In this section, the efforts at NIST to address this shortcoming are discussed.

### A. SSM: Presence Detection and Localization

The use of SSM for collaborative operations is intended to maintain a safe distance between the human and the robot. When triggered, the robot must come to a controlled stop prior to making contact with a person by taking into account the total distance traveled by both. The instantaneous separation distance, $S$, at time $t_0$ is dictated by the equation

$$S\left(t_0\right) \geq \begin{array}{l} \displaystyle\int_{\tau=t_0}^{\tau=t_0+T_R+T_S} v_H\left(\tau\right)d\tau + \\ \displaystyle\int_{\tau=t_0}^{\tau=t_0+T_R} v_R\left(\tau\right)d\tau + \\ \displaystyle\int_{\tau=t_0+T_R}^{\tau=t_0+T_R+T_S} v_S\left(\tau\right)d\tau + \\ \left(C+Z_S+Z_R\right) \end{array}, \quad (1)$$

where $v_H$ and $v_R$ are the velocities of the human and robot, respectively, and $v_S$ is the directed velocity of the robot along the stopping path. The variables $T_R$ and $T_S$ capture the time for the robots to respond to the presence of a human, and the time required to stop. System uncertainty is captured by 1) $C$,

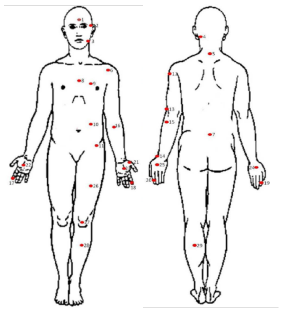

Fig. 1. The full-body model of pressure and force limits from [3].

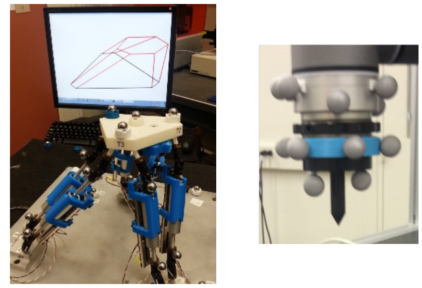

Fig. 2. The poses of robots and parts are measured directly using physical platforms (left) and markers tracked via motion-capture systems (right)

an intrusion distance safety margin based on statistically expected human reach [4], 2) $Z_S$, the sensing uncertainty of the safety system, and 3) $Z_R$, the robot positioning uncertainty. A detailed analysis of the SSM algorithm and recommendations regarding its application are presented in [5].

NIST has focused on the modeling of uncertainty of sensor systems that measure human and robot positions [6], [7], and their integration into the robots' controllers [8], [9]. In a related study on the gaps in the standards for mobile, industrial robot safety [10], a general concern was raised with regards to the state of safety-rated sensors for human detection. Sensors must adhere to specific performance criteria, including mechanisms for the V&V of sensing performance. However, the artifacts specified in the associated standards are not biomimetic. Also, the sensors detect only the presence of objects that have similar sizes of parts of the human body, but not human-specific.

NIST is developing sensor systems designed specifically to identify and localize humans in flexible factory environments. The sensor platform combines cameras that operate in multiple spectra (specifically, RGB and near-infrared), calibrated together for stereoscopic sensing. The cameras are segmented separately to compensate for the limitations of one another (e.g., using thermal to provide information in low-contrast/light color scenes, and using color to correct for thermally noisy scenes). A key challenge in configuring this system, however, is the calibration of the thermal-RGB pair. A traceable-calibration and performance-verification methodology based on [11] is being developed.

### *B. PFL: Dynamic Force Metrology*

With the expectation that physical contact will be made between a human and an active robot, PFL is intended to ensure that the transfer of pressures and forces do not result in injury. ISO/TS 15066 provides specifications for the shape and surface area of robots and tooling to minimize risk, and includes a full body model (Fig. 1) of pressure and force limits based on the onset of pain. In early drafts of the TS, specifications for a sensor system for the V&V of PFL were based on an earlier technical report [12]. NIST provided an analysis of these specifications [13], and called into question their feasibility, in particular with regards to sensor calibration for the measurement of dynamic forces. This issue was later addressed in an unrelated effort at NIST [14].

Today, collaborative robot systems do not provide sufficient pressure/force sensing at the points of contact. Most robot systems rely on joint-level current monitoring paired with gravity models to infer contact forces. As the mass of the robot increases, so too does the inherent noise in the force inference. Moreover, most tooling and onboard support equipment (e.g., cables and hoses) provide no sensing at all. As such, sensors that are reliable, lightweight, easily-integrated, and low-noise are expected to dramatically improve PFL performance. On these lines, efforts in NIST's Performance Assessment Framework for Robotic Systems project [15] seek to produce new test methods for assuring PFL performance. And development of bio-simulant artifacts [16] are expected to positively impact the accessibility and quality of *in situ* PFL V&V.

## III. Multi-Robot Coordination and Control

Being industry-focused, the robot-robot collaboration efforts at NIST are targeted toward enabling heterogeneous, multi-robot configurations to complete complex assembly tasks. Some robot systems take a negative performance hit in terms of accuracy and repeatability due to mechanical designs [17]. Nominal versus actual positions and orientations may reflect significant errors, so it is necessary to track the motions of the robots to accommodate these errors. Outside of high-cost laser systems used for one-off evaluations of position and path accuracy and repeatability [18], external sensor systems that monitor robot pose are ad hoc solutions with specific applications. Such systems not generally intended for coordinating robots, so multi-robot cells are reliant on direct communication of potentially noisy information for synchronization.

To compensate for issues preventing direct inter-robot communication in heterogeneous cells, NIST leverages external observer systems to 1) identify and track parts and robots, and 2) measure position and orientation uncertainty. These test methods directly influenced the work on evaluating and providing guidance toward improving multi-robot registration [17], [19] using a variety of sensor platforms, including motion capture systems (Fig. 2) and F/T transducers.

NIST's ongoing work is focused on developing new, active, metrology artifacts and sensor platforms for tracking robots and shared workpieces alike (Fig. 2). Moreover, NIST is investigating mobile industrial robot (robotic arms mounted on mobile platforms) coordination, and its impact on safety

[10] and process performance. A significant component of this includes issues regarding robot and sensor calibration and registration [20], [21].

## IV. Intuitive HRI

Emerging work at NIST is directed toward the advancement of HRI and human-machine interfaces. Using sensing to inform the robot systems of human-in-the-loop process performance, human attention, and human intention, NIST aims to develop new test methods to assess and assure the effectiveness of user interfaces and user experiences. Toward these efforts, both intrinsic and extrinsic robot and human sensing are leveraged, borrowing from the systems and results discussed in Sections II and III. These measurements are then processed and fed back to operators and robots via non-standard means to optimize situation awareness and reduce negative impacts on the team and process.

Small-scale and wearable technologies, in particular, are targeted as potential inputs to the human-robot-team observers. Wireless 9DoF IMUs, simple tilt sensors, light detectors, electromyographic inputs, and time-of-flight distance sensors are integrated into wearable sensor platforms (e.g., protective equipment), shared workpieces, and robot-mounted tools. Consumer products such as smart watches, head-mounted displays, and haptic gloves are also used as alternative interfaces to the robot systems. With the assumption of noisy or missing measurements, these ancillary platforms are then networked together, and the data fused to improve both the quality and the quantity of information to the collaborative team.

Since the provision and maintenance of situation awareness is a motivating concern for these efforts, the presentation of reliable and understandable information is the primary focus. Non-standard interfaces such as augmented and virtual reality displays paired with real-time digital models and $360^o$ video naturally fit into this effort. These interfaces provide intuitive mechanisms for both feedback and control, enabling two-way communications regarding robot and operator performance, attention, and intent. This then propagates naturally into state representations of the process and the human-robot team, in turn improving performance and safety [22].

## V. Discussion

This report briefly discusses the ongoing research at NIST involving the novel application of sensors for safe, collaborative HRI. Many challenges and opportunities for the ongoing development of applied sensor systems were briefly described. Worth reiterating here is the need for providing thorough V&V methodologies to such sensor systems. “Hardening” systems to ensure robustness in harsh manufacturing environments is important, but ensuring that the uncertainties and limitations of sensor systems are known is critical when integrating prototype or one-off systems into human-occupied workcells.

## Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

## References


[1] E. Messina. (2017) Robotic systems for smart manufacturing program. [Online]. Available: ” https://www.nist.gov/programs-projects/robotic-systems-smart-manufacturing-program”

[2] J. Marvel. (2017) Performance of collaborative robot systems. [Online]. Available: ”https://www.nist.gov/programs-projects/performance-collaborative-robot-systems”

[3] “ISO/TS 15066 Robotics and robotic devices - Collaborative robots,” International Organization for Standardization (ISO), Standard, 2016.

[4] “ISO 13855 Safety of Machinery - Position of Safeguards with Resepect to the Approach Speeds of Parts of the Human Body,” ISO, Standard, 2010.

[5] J. A. Marvel and R. Norcross, “Implementing speed and separation monitoring in collaborative robot workcells,” *Rob. Comput.-Integ. Manuf.*, vol. 44, pp. 144–155, 2017.

[6] W. Shackleford, R. Norcross, J. Marvel, and S. Szabo, “Integrating occlusion monitoring into human tracking for robot speed and separation monitoring,” *Proc. Worksh. Perf. Metrics Intel. Syst.*, pp. 168–173, 2012.

[7] J. A. Marvel and R. Bostelman, “A cross-domain survey of metrics for modelling and evaluating collisions,” *Int. J. Adv. Rob. Syst.*, vol. 11, no. 9, p. 142, 2014.

[8] J. A. Marvel, “Performance metrics of speed and separation monitoring in shared workspaces,” *IEEE Trans. Autom. Sci. Eng.*, vol. 10, no. 2, pp. 405–414, 2013.

[9] W. Shackleford, G. Cheok, T. Hong, K. Saidi, and M. Shneier, “Performance evaluation of human detection systems for robot safety,” *J. Intell. Rob. Syst.*, vol. 83, no. 1, pp. 85–103, 2016.

[10] J. Marvel and R. Bostelman, “Towards mobile manipulator safety standards,” *Proc. IEEE Int. Symp. Rob. Sens. Env.*, pp. 31–36, 2013.

[11] A. K. Krishnan and S. Saripalli, “Cross-calibration of rgb and thermal cameras with a lidar for rgb-depth-thermal mapping,” *Unmanned Syst.*, pp. 1–20, 2017.

[12] D. G. Unfallversicherung, “Bg/bgia risk assessment recommendations according to machinery directive, design of workplaces with collaborative robots,” Report, Tech. Rep., 2009.

[13] J. Falco, J. A. Marvel, and R. Norcross, “Collaborative robotics: Measuring blunt force impacts on humans,” *Proc. Int. Conf. Safety Indust. Autom. Syst.*, 2012.

[14] N. Vlajic and A. Chijioke, “Traceable dynamic calibration of force transducers by primary means,” *Metrologia*, vol. 53, no. 4, p. S136, 2016.

[15] E. Messina. (2017) Performance assessment framework for robotic systems. [Online]. Available: ”https://www.nist.gov/programs-projects/performance-assessment-framework-robotic-systems”

[16] N. G. Dagalakis, J.-M. Yoo, J.-M. Yoo, T. Oeste, and T. Oeste, “Human-robot collaboration dynamic impact testing and calibration instrument for disposable robot safety artifacts,” *Indust. Rob.: An Int. J.*, vol. 43, no. 3, pp. 328–337, 2016.

[17] J. A. Marvel and K. Van Wyk, “Simplified framework for robot coordinate registration for manufacturing applications,” *Proc. IEEE Int. Symp. Assembly Manuf.*, pp. 56–63, 2016.

[18] “ISO 9283 Manipulating industrial robots Performance criteria and related test methods,” ISO, Standard, 1998.

[19] K. Van Wyk and J. A. Marvel, “Strategies for improving robot registration performance,” *IEEE Trans. Autom. Sci. Eng.*, In Press.

[20] R. Bostelman, R. Eastman, T. Hong, O. Enein, S. Legowik, and S. Foufou, “Comparison of registration methods for mobile manipulators,” *Proc. Int. Conf. Climbing Walking Rob.*, pp. 205–213, 2016.

[21] S. Legowik, R. Bostelman, and T. Hong, “Sensor calibration and registration for mobile manipulators,” *Proc. 5th Int. Conf. Adv. Vehic. Syst., Techn. Appl.*, 2016.

[22] J. A. Marvel, J. Falco, and I. Marstio, “Characterizing task-based human–robot collaboration safety in manufacturing,” *IEEE Trans. Syst., Man, and Cybern.: Syst.*, vol. 45, no. 2, pp. 260–275, 2015.