Final Project Report

Standards for Metrology Assisted Robot Technology (SMART)	
Principal Investigator / Email Address	Joshua Johnson
Project Team Lead	The Boeing Company
Project Designation	MxD-19-02-01
MxD Contract Number	2020-01
Project Participants	Missouri Science & Technology, Automated Precision Incorporated, Georgia Tech Research Corporation, and Hexagon Metrology
MxD Funding Value	N/A
Project Team Cost Share	N/A
Award Date	June 4, 2020
Completion Date	December 30, 2022

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MxD PROJECT FINAL REPORT SUMMARY

MxD 19-02-01: Standards for Metrology Assisted Robot Technology SMART

MxD Project Close Out Summary | May 4, 2024

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I. EXECUTIVE SUMMARY

The future success of Original Equipment Manufacturers (OEMs) of large assemblies significantly depends on the capability to automate more processes using low-cost industrial robots (IR). However, many limitations exist that hinder the viability of using COTS IRs for manufacturing process that require high geometric accuracy over a large volume or subject to dynamic loading from process forces. The factors limiting the use of IRs in such processes can be traced to three major sources of error, joint position, kinematic, and non-kinematic. Kinematic error has been studied exhaustively and many techniques exist to correct this error; Boeing published several related papers.[1] Non-kinematic error presents significantly more challenges that Boeing and team has years of experience in reducing through novel methods of modeling, compensation, and optimizations. [2]

During this project, the team created and evaluated novel approaches to improving the task performance of an IR with metrology feedback or Metrology Assisted Robot (MAR). The team included two facilities located on the campuses of Missouri Science & Technology and Georgia Institute of Technology (Figure 1). Evaluating the performance of each system with a common approach was critical in determining the best achievable geometric accuracy. Therefore, the team created an expanded document consisting of specific testing methods and nomenclature for a MAR system using existing robotic testing standards.

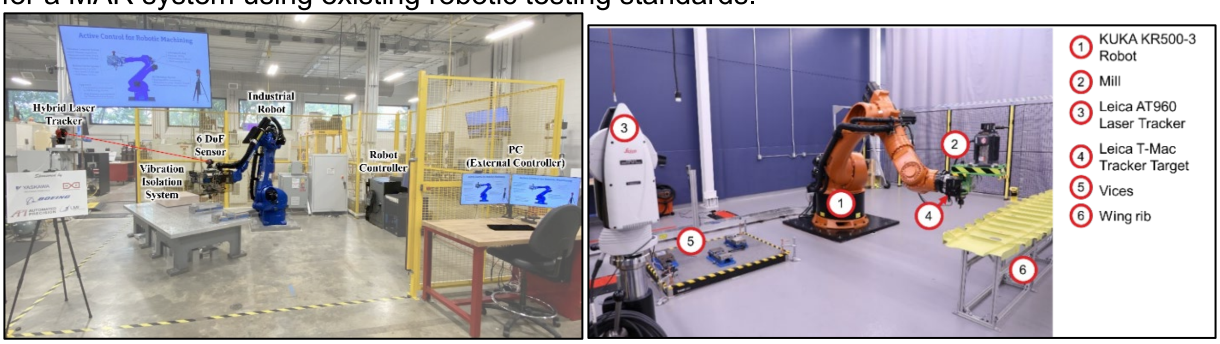

Figure 1: MAR system at Missouri Science & Technology (left) & Georgia Institute of Technology (right)

Each location used different hardware to build their MAR, which insured the testing methods were hardware agnostic. Using two test facilities proved vital in the development of system architecture and control methods, as each team presented significantly different approaches. In addition, each team presented an accuracy improvement method outside of the MAR feedback loop. MS&T developed an end effector aimed at reducing the vibration induced by milling and GaTech developed algorithms for optimization of robotic pose and control gains. The geometric performance achieved by the team using the Indicated Flatness testing procedure was ±135μm.

[1] Freeman, Philip. A novel means of software compensation for robots and machine tools. No. 2006-01-3167. SAE Technical Paper, 2006.

[2] US6392222, US6980881, Greenwood, Thomas A., and Thomas W. Pastusak. Optical End-Point Control for NC Machinery. No. 972253. SAE Technical Paper, 1997.

The software used to evaluate the improvement methods of the MAR system are available on an MxD hosted repository. For associated project documentation or questions please contact MxD at project@mxdusa.org.

II. GENERAL PROJECT INFORMATION

	Description	
Project Name	***Standards for Metrology Assisted Robot Technology***	
Project Description	During this project, the team created and evaluated novel approaches to improving the task performance of an IR with metrology feedback or Metrology Assisted Robot (MAR). The team included two facilities located on the campuses of Missouri Science & Technology and Georgia Institute of Technology (Figure 1). Evaluating the performance of each system with a common approach was critical in determining the best achievable geometric accuracy. Therefore, the team created an expanded document consisting of specific testing methods and nomenclature for a MAR system using existing robotic testing standards.	
Technology Developed	Standards MAR	**Program:** **Thrust Area:** Future Factory
Project Lead	Boeing	**Principal Investigator:** Joshua Johnson
Other Project Participants	Missouri Science & Technology Automated Precision Incorporated Georgia Tech Research Corporation Hexagon Metrology	**MxD Program/Project Manager:** Wildaline Serin
Project Funding		**Project Start Date:** June 4, 2020 **Project End Date:** November 1, 2022
Technology Readiness Level	*TRL6*	

a. Project Background	
PROJECT CALL 19-02: CLOSED-LOOP, MEASUREMENT CONTROL FOR ENHANCED ROBOTIC PERFORMANCE	
Project Call Release Date	August 2019

Project Call Goal	Develop new manufacturing capabilities in the area of closed-loop robotic control.

b. Project Goal Statement

This project looks to fund the development of a flexible manufacturing system that utilizes sensor and metrology technology for closed-loop, precision robotic milling.

c. Specific Industry Problem or Challenge being addressed by the Project

Traditional precision machining methods require extensive capital investments and lack the adaptability to changing production needs. Industrial robots have shown adaptability to other use cases on the factory floor, but their kinematic variability and stiffness present accuracy challenges for processes like milling where there is extensive, dynamic loading.

d. How was the Problem addressed

Created and evaluated novel approaches to improving the task performance of an IR with metrology feedback or Metrology Assisted Robot (MAR).

e. Summary of Project Outcomes

The team created and evaluated novel approaches to improving the task performance of an IR with metrology feedback or Metrology Assisted Robot (MAR). The team included two facilities located on the campuses of Missouri Science & Technology and Georgia Institute of Technology.

f. Final Project Deliverables

Standard Proposals Development
Generate industrial standard proposals to facilitate broader industry use and lay the framework for an interoperable system architecture.
Control Algorithm Development
Develop an algorithm(s) that will digest sensor/metrology/kinematic data and compensate for any transmission latency to provide path correction under dynamic loading conditions.
Trajectory Controller Development
Develop an external trajectory controller that employs a runtime software with modules for the devised algorithms and provides real-time path correction to the robot controller.
System Integration and Test
Integrate the developed technologies per the created standards on a system testbed and demonstrate its effectiveness for precision machining.

III. KPI's + METRICS

Metric	Baseline	Goal	Results	Validation Method
Trajectory Accuracy	±1000μm	±250μm	±102μm MS&T	Trajectory Accuracy
Capital Cost	>$1,000,000	<$300,000	~$500,000	Standard pricing

Scale	<3m	1.5x7m	1.5x7m	Discrete testing throughout task space
Cycle Time	Non-real-time performance	<1ms	1ms	Manufacturer specifications

IV. INDUSTRY IMPACT + POTENTIAL

a. Impact to the specific market the project was addressing and size of that market

This technology has the benefit of allowing more commonly available industrial robots to performance tasks with better geometric accuracy and on larger geometric scale.

b. How this could be used in other industries

This technology can be used to improve the geometric accuracy performance of any computer-controlled equipment.

c. Next Steps based on other use potential

Publication by ASME

V. ACCESSING THE TECHNOLOGY

a. Background Intellectual Property

Commonly available standards

b. Technical and System Requirements

Spatial modeling software e.g. Spatial analyzer, polyworks, etc.

VI. ADDITIONAL COLLABORATION OPPORTUNITIES

The Principal Investigator is interested in further collaborating with MxD members in the following ways:
Collaboration between ASME already exists and a small effort is needed to get the project outcomes published
☐ Case studies to further test technology ☐ Further develop technology outcomes (advance TRL) ☐ Utilize MxD Partner Innovation Projects platform ☐ Commercialization partner ☐ Venture funding ☒ Other