Modeling Performance Measurement of Mobile Manipulators

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***Abstract*- Mobile manipulators are being marketed around the world as single manufacturer systems (i.e., robot arm and vehicle manufactured by the same organization) and as independent robot arms, from a different manufacturer and integrated with automatic guided vehicles (AGVs) or mobile robots. Test methods for measuring safety and performance of either of these types of mobile manipulators have yet to be developed and therefore, potential users cannot compare one system to another to match to tasks. Similarly, the control of these systems can vary greatly from AGV control to more autonomous mobile robot control and further, to robot arm control methods. Systems Modeling Language (SysML)[1] is a general-purpose modeling language for systems engineering applications that supports the specification, analysis, design, verification, and validation of simple through complex systems, such as mobile manipulators. This paper uses SysML to describe a method using an artifact for performance measurement of mobile manipulators performing assembly tasks. Uncertainty propagation, a key component in understanding the effects of mobile manipulator constraints, is also modeled and described.**

I. Introduction

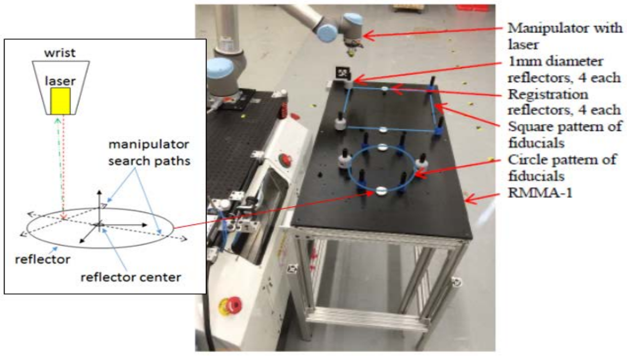
Future smart manufacturing systems will include more complex coordination of systems, such as mobile manipulators (i.e., robot arms mounted on mobile bases). Mobile manipulators expand the fixed robot automation of the past into more flexible and capable robots. "Mobile manipulators offer high mobility and manipulability. An ideal utilization of the motion redundancy in the mobile manipulator is to perform assembly tasks on a moving vehicle body while tracking." [1] Mobile base (e.g., automatic guided vehicle (AGV) or mobile robot) and onboard manipulator functionality and performance specifications should be provided by the manufacturer so that the user can match the system to the task, such as assembly or welding tasks. However, to date there are no standard performance measurement methods published so that all mobile manipulator manufacturers can provide similar performance data to the potential system user. Additionally, mobile manipulator control must be known so that users can rapidly and cost effectively program the system to perform as expected. As any quick search on the internet can provide, there are many programming languages available today and used to control robots, for example: Robot Operating System (ROS), LISP, Assembly, MATLAB, C#/.NET, Java, Python, and C/C++ to name a few. Just as there is a need for a standard performance measurement test method for measuring mobile manipulators, there should also be a standard robot control, as well as modeling, language for use within the test method allowing standard representation of the system under test.

Model Based Systems Engineering (MBSE) provides a simplified representation of a system. Specifically, Systems Modeling Language (SysML) is a graphical modeling language that supports the "specification, analysis, design, verification, and validation of systems that include hardware, software, data, personnel, procedures and facilities." [2] SysML provides four essential tools, also called pillars: Structure (with definition and use), Behavior (with interaction state machines, and activity/function), Requirements, and Parametrics (with equations and units). Rahman, et al [3] say that using SysML can enable the creation of reusable software modules for programming the robot to allow platform independent design and reduced development time. Additionally, Rahman, et al also suggest that SysML is uniquely suited for both accurately modeling increasingly complex and physical robotics systems, as well as the standardization of such an approach useful across many different industries.

Measurement of the robot's Cartesian pose, which is combined with the mobile base's pose, is relatively complex where the system can include nine or more degrees of freedom. To simplify measurement, an artifact was designed to allow various geometric patterns to be traced by the robot wielding a tool point sensor to sense the dimensional points along the patterns. The artifact was designed and manufactured to include a flat surface with embedded geometric patterns to trace allowing for different mobile manipulator performance measurement scenarios. The scenarios include: A) static: the AGV stops while the robot accesses all points within its work volume, B) indexed: the AGV initially stops while the robot accesses most points within its work volume, informs the AGV to increment to a new point, and to stop while the robot accesses the remaining points, and C) dynamic: both the AGV and robot simultaneously move while the robot accesses all points.

[1] Commercial equipment, software, and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials, equipment, or software are necessarily the best available for the purpose.

This paper applies SysML modeling to the performance measurement of mobile manipulators. The SysML models are



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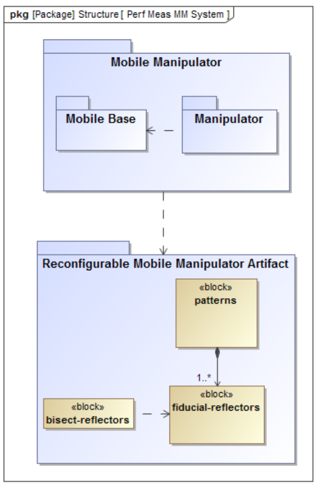

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Fig. 1 – (a) NIST mobile manipulator and artifact with left inset showing the Bisect search path using the laser retroreflector. (b) SysML package diagram showing the mobile manipulator and measurement artifact structures.

verified through review of the systems being used in this iteration, including the mobile base (AGV), manipulator (robot arm), and an artifact measurement system. Previous experiments have occurred [5] that also verify the mobile manipulator performance measurement concepts modeled in this paper. The paper first considers the mobile base and onboard manipulator systems in block definition and internal block diagrams showing their interconnections. Similarly, the artifact measurement system used to measure performance is then modeled and described. Following is a discussion on the uncertainty propagation for the performance measurement of mobile manipulators, as well as a description of an example use case model within a production facility.

II. Mobile Manipulator System

An example mobile manipulator system used as basis for this paper is shown in Fig. 1 (a). The system is used for developing mobile manipulator performance test methods and for uncertainty measurements under the National Institute of Standards and Technology (NIST) Robotic Systems for Smart Manufacturing Program [6]. This program provides "the measurement science needed to enable all manufacturers, including small and medium ones, to characterize and understand the performance of robotics systems within their enterprises." The mobile manipulator shown in Fig. 1 (a) provides a collaborative robot measurement platform who's position and orientation (pose) of the mobile base relies on reflectors mounted on the surrounding walls or within the AGV world. The robot arm or manipulator is mounted on the AGV top-front. An artifact that was developed at NIST, called the reconfigurable mobile manipulator artifact (RMMA), and was used for measuring the mobile manipulator as a novel and relatively low cost method.

Fig. 1 (b) shows a SysML package model of the described systems. This high-level model, to be detailed in the following sections, provides an overview of the systems that make up the mobile manipulator and RMMA. The RMMA is shown to include two main components: a bisect-fiducial block that is used for registration of the mobile manipulator to the RMMA and a fiducial-reflector block that can include one or many to make up patterns used to test the mobile manipulator.

The mobile base is an AGV manufactured with the industry's pseudo-standard controller and software, shown on the left side of Fig. 2, as parts to the AGV controller-offboard block. Within the AGV controller-offboard lists the software used to control the vehicle and residing in this offboard computer. This example vehicle has many of the same components found in autonomous industrial vehicles with navigation sensors (Nav sensor) that may or may not require facility reflectors. If the vehicle uses simultaneous localization and mapping (SLAM), features of the facility would be shown in place of the Facility reflectors block. Steer and Drive motors and amplifiers, and batteries are also typical. In the experimental case provided in this paper, there is also an offboard manipulator controller (Manipulator controller-offboard) which may not be typical of industry as all manipulator control may be onboard the vehicle.

The manipulator block definition diagram, shown on the right side of Fig. 2, has a similar component layout as for the AGV with motors/amplifiers, encoders, and an onboard and offboard controller. Additionally, an end-of-arm tool (EOAT) is shown that includes a laser retro-reflector tool. The Manipulator controller-offboard provides the connection to the onboard AGV controller (CVC600) and lists associated software parts (part is a SysML term for subcomponent).

However, it is essential that the independent AGV and onboard manipulator controllers communicate their poses (position and orientation), in this case relative to the AGV world (facility reflectors). There has been a lot of research in centralized and decentralized offboard robot-to-robot communication [7] and combined controller communication [8], although there is little discussion of combined, yet independently controlled, mobile base and manipulator control communication methods in the literature. The manipulator also can also share power from batteries as shown in the figure.

mm step sizes will take much longer to find the reflector center verses a 2 mm step size, although with much less accuracy.

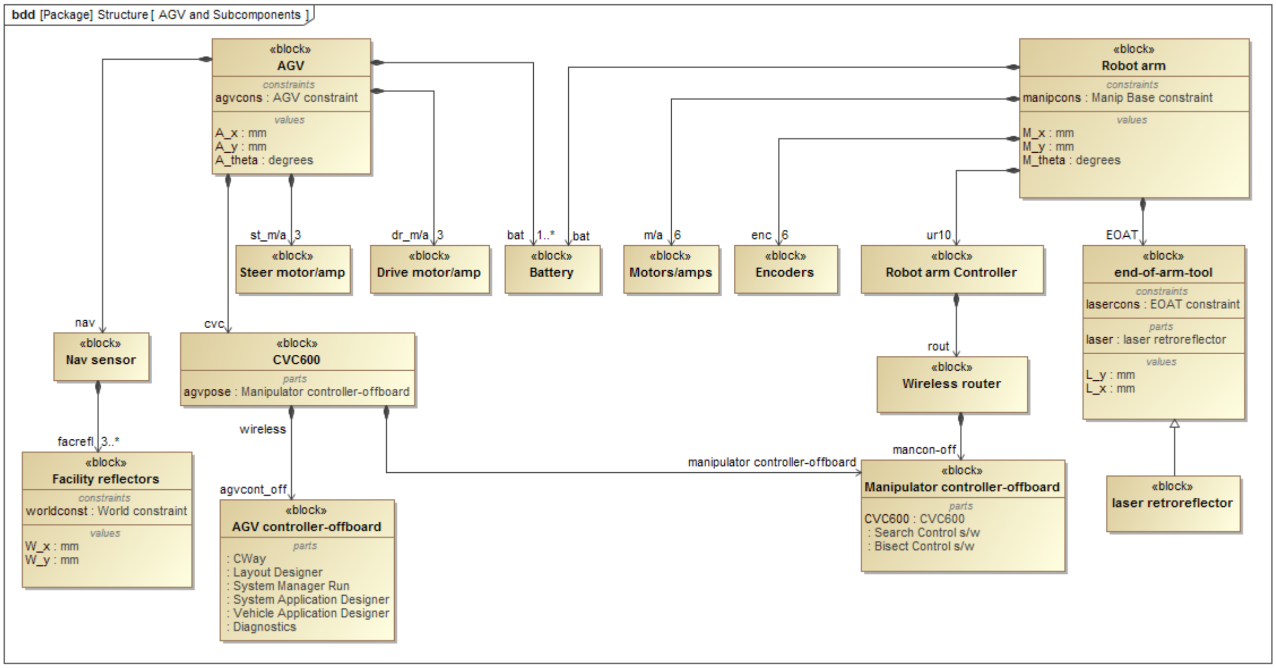

Fig. 2 – SysML internal block diagram of the mobile manipulator subcomponents. The AGV and Robot arm each have independent onboard components with only power (battery) linking them together. Offboard controllers also list the programs (parts) that control their associated systems (e.g., AGV).

The manipulator internal block diagram shown in Fig. 2 also includes an additional constraint of tool positioning along with the base mounting constraint (Manip Base constraint). This part constraint describes the mounting uncertainty that can occur when the manipulator is mounted to the mobile base. And, although the AGV is linked to the Robot arm part due to the onboard manipulator mount, the AGV includes its additional constraint of pose uncertainty. These will be further detailed in section IV. Uncertainty Propagation.

Fig. 3 shows an internal block diagram of the software algorithms that control the manipulator during performance measurements. The indexing test (B) described in section I is modeled. On the lower right are one hardware part (CVC600) and two software parts from the AGV (System Manager Run and CWay). The manipulator is dependent upon the System Manager Run program informing the manipulator of the AGV pose when parked at the RMMA. The manipulator performs intermediate motions to a manipulator base pose that causes the manipulator to approach the Bisect Control (see Fig. 1 (a) left inset) and Search Control registration points on the RMMA in the same way. This ensures the manipulator will not attempt to pass the EOAT through the robot base or perform other self-destructive motions.

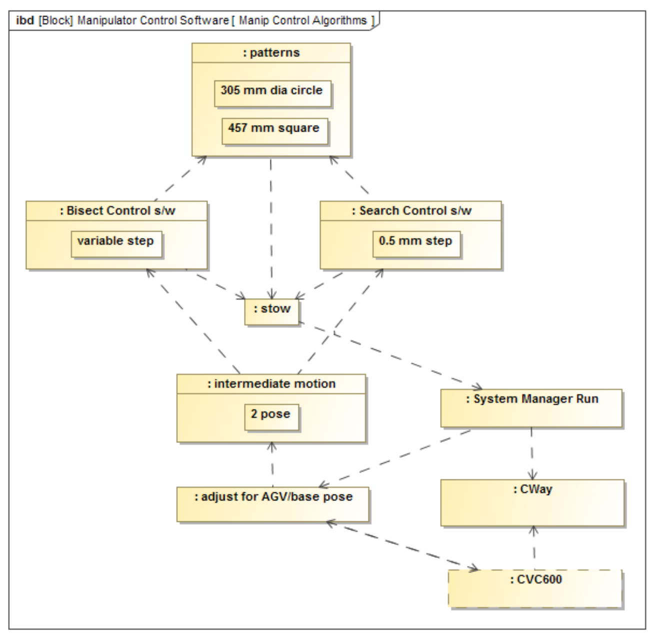

Figure 3 – SysML internal block diagrams of the manipulator control software components.

Dependent upon the stakeholder (e.g., test requestor) selection of performance measurement type, either the bisect or search method, or both are performed. Step sizes for the Bisect Control are left variable allowing the operator to choose the time for the manipulator to bisect to find the large reflector center and/or the accuracy of the center. For example, a 0.25

Similarly, when using only the Search Control for registration to the RMMA, a very small step size provides relatively higher accuracy. However, a step size of half the diameter of fiducial reflector was determined an ideal step size to maximize accuracy measurement and minimize search time. For example, when 1 mm fiducial diameters were used, the 0.5 mm step size was used. Based on the AGV location, either the circle or square pattern is then traversed. Stowing the manipulator was programmed to occur when the pattern was completed or when performing Bisect Control or Search Control that did not produce appropriate results within a chosen time period. For example, if the Bisect Control did not initially result in a reflector detect or if the Search Control took more than 200 steps, the manipulator Stow function was executed and the AGV System Manager Run program was alerted that the AGV could move. A smaller number of steps could also be used.

III. Performance Measurement Artifact

Metrology methods for measuring performance of mobile manipulators, with technologies used to access parts or assemblies in manufacturing processes, listed in [9], include: physical contact using a touch probe, cameras detecting fiducials, laser interferometry, theodolites, coordinate measuring arms, path comparison, trilateration, polar coordinate measuring, triangulation, optical tracking, inertial measuring, Cartesian coordinate, and path drawing.

This section provides an alternative to these methods by using the RMMA with non-contact measurement using a laser retroreflector. This method could potentially prove cost effective while providing the desired maximum uncertainty for mobile manipulator performance measurement. The RMMA is expected to be used within a standard test method to measure the performance of static and mobile manipulators. By comparison, it is estimated that the use of the RMMA could be 20 times lower cost than the use of, for example, an optical tracking system. The RMMA is a metal plate with fiducial mount points at precise locations. The RMMA, shown in Fig. 1 beside the mobile manipulator, could also be made using additive manufacturing and estimated to further reduce costs by another order of magnitude. Reflective fiducials are to be detected using a laser retroreflector detector, carried by the manipulator as the EOAT, passing through a collimator attached to the RMMA. A 305 mm (12 in) diameter circle pattern and a 457 mm (18 in) square pattern of fiducials are machined with 0.025 mm (0.001 in) tolerance into the RMMA. Other components are also part of the RMMA where all components are modeled in a SysML internal block diagram shown in Fig. 4.

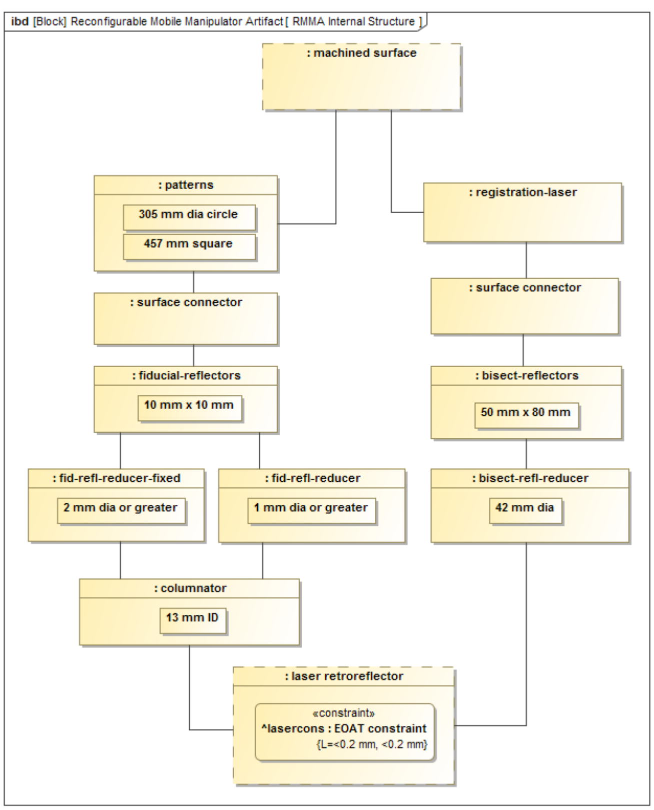

Figure 4 – SysML internal block diagram showing the reconfigurable mobile manipulator artifact (RMMA) structure.

Beginning at the laser retroreflector (Fig. 4, bottom-left), a positioning constraint is applied to the EOAT provided by the robot manufacturer specification. Moving up the left of the model, the collimator has a 13 mm inside diameter limiting the EOAT angle relative to the RMMA where fiducial detection can occur. The collimator is attached to two different types of fiducial reducers ('fid-refl-reducer-fixed' with a fixed reflector diameter of 2 mm or greater, depending on the EOAT uncertainty chosen, and a 'fid-refl-reducer' with a variable reflector diameter of 1 mm or greater that uses an optical aperture to minimize diameter to the center of the reflector). Both of the fiducial reducers are above 10 mm square fiducial-reflectors and attached to the RMMA through surface connectors into circle and square patterns embedded in the machined surface of the RMMA.

Since the mobile manipulator may or may not already be registered to the RMMA, a means is needed to allow this registration. The Fig. 4-left modeled parts can be used for mobile manipulator registration with the RMMA using search methods where the fiducial locations are previously taught. A second set of parts is also modeled in Fig. 4 - right showing the laser retroreflector being used to detect 42 mm diameter reflectors (bisect-refl-reducer) for an alternative mobile manipulator-to-RMMA registration method. The 42 mm diameter was chosen so that the EOAT would always detect these reflectors and a control method, called bisect and shown in the inset of Fig. 1 (a), could be used for the registration process. In other words, as the mobile manipulator indexes from one pose to the next, the vehicle pose combined with the robot arm pose would always detect the large reflector. Off-the-shelf 50 mm x 80 mm rectangular reflectors (bisect-reflectors) were covered by the square-to-round 42 mm opening bisect-refl-reducer and mounted to the RMMA using surface connectors at initially taught manipulator locations (registration-laser) on the machined surface.

IV. Uncertainty Propagation

As a preliminary notion, the world within which a mobile base, such as an AGV, should be measured and provided to the vehicle controller as reference. The vehicle pose will only be as accurate as its reference. Therefore, AGV calibration is essential to enable higher accuracy and repeatability for the mobile manipulator which references the robot base pose to its mobility system or, in this case, AGV.

A typical method of measuring reflector locations in the world is to use a metrology system, such as a surveyor's tool (i.e., approximately 1.5 mm uncertainty over 1.5 km [10]) or a laser tracker (i.e., approximately 18 µm uncertainty over 12 m [11]). The authors chose the laser tracker so that the AGV reference to the world would be relatively more accurate. An onboard, spinning, navigation laser range and azimuth sensor then provides pose information to the vehicle controller. One issue (i.e., first major uncertainty point (AGV)) with the AGV control is that it uses the measured pose with respect to the world (facility reflectors) and the AGV control reference location is at floor level, at the vehicle centroid (i.e., beneath the vehicle). As such, this location is very difficult to use as a measurement reference.

The robot arm is mounted on a machined breadboard with 51 mm spaced, threaded holes and the robot arm is mounted to the breadboard with a machined interface plate. There is some uncertainty as to how accurately the breadboard is mounted with respect to the AGV reference point and causing a second uncertainty point (Manip Base). The third uncertainty point (EOAT) is the relative accuracy of end-of-arm-tool pose of the carried laser that the robot arm is capable of providing. The uncertainty propagation can therefore be modeled as World which combines the constraints (AGV, Manip Base, and EOAT constraints) and can then be modeled in a block definition diagram, as shown in Fig. 5, which allows each of their constraint parameters to be clearly displayed. Also, the parameters for each of the constraints and interconnects that produce the uncertainty propagation are shown in the figure which can be described in the matrix equation:

$$ {}_{W}P_{E} = {}_{W}H_{A} * {}_{A}H_{M} * {}_{M}P_{E} \qquad (1)$$

where: P represents points, H represents rotation and translation vectors or sets of 3 x 3 homogeneous equations, W = World, E = EOAT, A = AGV, and M = Manipulator. A SysML parametric diagram, not included here, can then be used to further display the equations within a model.

V. USE CASE

Up to this point, the mobile manipulator system and the measurement system have been modeled, including the uncertainty propagation that can occur from performance measurements. SysML models are therefore needed to show how this information would be useful when applying the mobile manipulator performance measurement concept. Four

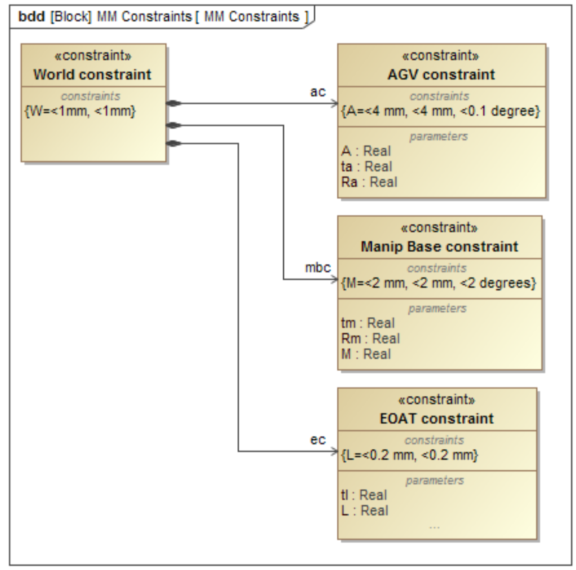

Figure 5 – SysML (a) block definition diagram showing the constraints that lead to uncertainty propagation for a mobile manipulator.

models (activity, sequence, state, and use case) are useful to show all aspects of the production case. For this paper and to only demonstrate the modeling concept, a use case diagram is provided.

Fig. 6 shows a SysML use case diagram modeling the process that represents a production facility where a mobile manipulator is used normally from "Execute MM operations with production facility" to "Continue normal production operations". Additionally, and in parallel to normal operation, is the mobile manipulation measurement task. The model shows that the mobile manipulator can also be sent from the production area to "Execute mobile manipulator performance measurement test" within a calibration area "MM (mobile manipulator) System and Measurement Systems package". The mobile manipulator is adjusted upon calibration (violet task), and then returned to "Continue normal production operations". To be thorough, the addition of the three actors (with blue heads) were also needed to perform tests during the author's experimental research. The use of the RMMA (yellow tasks) is dependent upon the stakeholder's requirements for mobile manipulator accuracy and cost. In the research use case, there is of course, no return of the system back into production. Also, it is expected that the 'Adjust MM (mobile manipulator) parameters based on performance tests' task would be performed automatically. However, in a test case, maintenance staff or researchers would log the data and suggest that it passes or fails the performance measurement test.

VI. CONCLUSIONS

Mobile manipulators are relatively complex tools that are now capable of performing manufacturing assembly tasks. Experiments at NIST and referenced in this paper suggest that their uncertainty has been shown to be within 1 mm. The complexity of these systems are exemplified in their

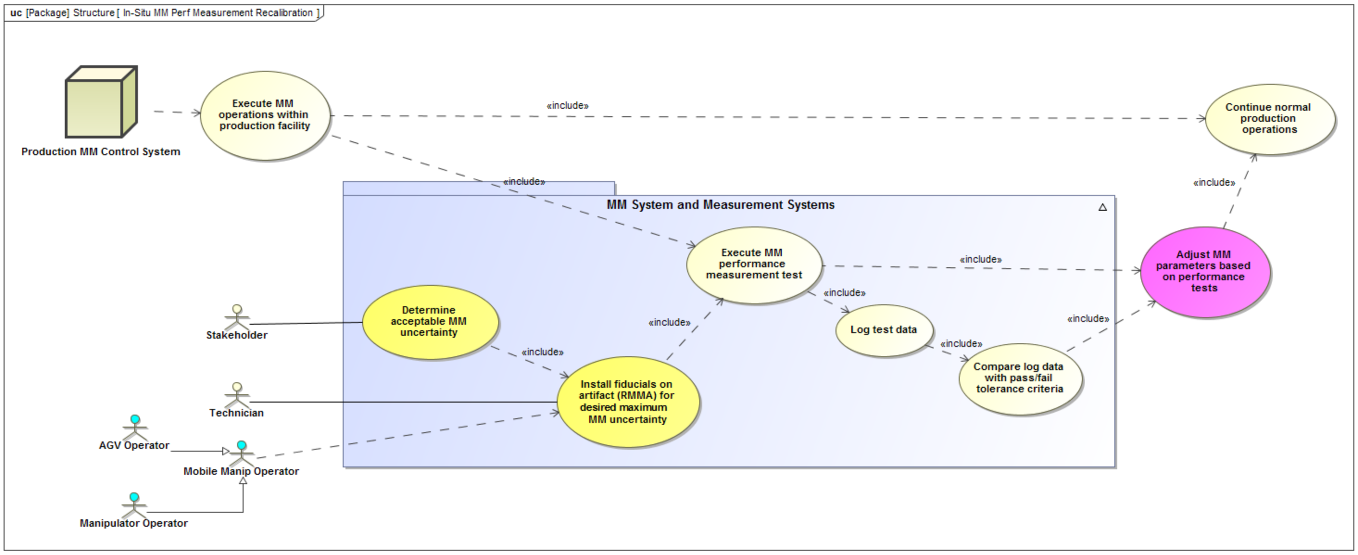

Figure 6 – SysML use case diagram of the RMMA (yellow tasks) used to measure performance of a mobile manipulator as may be found in a production facility during operation. The addition on the three blue head actors were required during research and are not required for a production case.

subcomponents (e.g., controller, navigation sensor, amplifiers, wheel/joint encoders, etc.) and the number of degrees of freedom to be controlled. SysML provides a useful method to model, not only the internal subcomponents that make up mobile manipulators but also, the control algorithms.

A test method to measure the performance of mobile manipulators is also critical for users to match the capability of these systems to assembly and other tasks. However, no safety or performance tests are currently standardized for these systems. A novel artifact, called the reconfigurable mobile manipulator artifact (RMMA), has been designed and used at NIST through experimentation to prove the performance of mobile manipulators for assembly tasks. As with the control of these systems, their performance measurement can also be modeled using SysML. The outcome of the models can then show system or component constraints, uncertainty propagation, and use cases in a simple and standardized way.

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