Control Fusion for Safe Multi-Robot Coordination

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ABSTRACT

Future smart manufacturing systems will include more complex coordination of mobile manipulators (i.e., robot arms mounted on mobile bases). The National Institute of Standards and Technology (NIST) conducts research on the safety and performance of multiple collaborating robots using a mobile platform, an automatic guided vehicle (AGV) with an onboard manipulator. Safety standards for robots and industrial vehicles each mandate their failsafe control, but there is little overlap between the standards that can be relied on when the two systems are combined and their independent controllers make collaborative decisions for safe movement. This paper briefly discusses previously uncovered gaps between AGV and manipulator standards and details decision sharing for when manipulators and AGVs are combined into a collaborative, mobile manipulator system. Tests using the NIST mobile manipulator with various control methods were performed and are described along with test results and plans for further, more complex tests of implicit and explicit coordination control of the mobile manipulator.

Keywords: mobile manipulator, safety, safety standards, test methods, control, coordination

1. INTRODUCTION

This paper (1) references and briefly discusses previously uncovered gaps in automatic guided vehicle (AGV) and industrial robot arm (hereafter termed 'manipulator') standards and (2) details decision sharing for when manipulators and AGVs are combined into a collaborative, mobile manipulator system. The National Institute of Standards and Technology (NIST) mobile manipulator was tested using independent, master/slave, and shared-model control. This paper summarizes both the performance results and their analysis for those tests. In closing, there will be a plan for testing implicit and explicit coordination control of the mobile manipulator.

In traditional manufacturing systems, process planning and product scheduling provide only a single sequence of operations to be executed for each product in the manufacturing process. Plaisanu, et. al., suggest that in situations where the product mix changes frequently or a greater flexibility of operations is required, new approaches are needed [1]. Klavins demonstrated a self-stabilizing robot supervisory system used to synchronize and schedule the movements of multiple robots [2]. Multiple robots used in concert for manufacturing typically have low-level motion control paired with high-level communication between robots. The supervisor receives information from the robot controllers regarding their status, and then, based on the status reports, issues instructions to the devices. While traditional manufacturing systems incorporate this multi-robot control within fixed cells, future smart manufacturing systems will include more complex coordination of mobile manipulators (robot arms mounted on mobile bases). Bøgh *et al.*, [3] provide examples and a timeline of the many mobile manipulator systems that have been or are being researched. In [4], Chen and Zalzala simulate the multi-criteria position and configuration optimization of a mobile manipulator, including least torque norm, manipulability, torque distribution, and obstacle avoidance, using genetic algorithms to search for optimal solutions. Planned or expected use-cases of each robot being coordinated must be clearly defined to develop safety test methods for potential inclusion in safety standards. A mobile manipulator that uses onboard sensors for navigation, handling components, and safety is discussed in Hvilshøj *et al.*, [5]. The research only briefly mentions the safety aspect of the coordinated robot system. Mobile manipulators are expected to perform tasks such as material handling of variable sub-assemblies and then assembling the parts into larger structures, perhaps side-by-side with humans and in frequently changed locations. The Computing Community Consortium's Robotics Roadmap [6] predicts

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that in 5 years we will have “inherently safe (hardware and software) professional mobile robots, with manipulation, operating in cooperation with trained humans in all professional environments,” including manufacturing.

The NIST Performance of Collaborative Robot Systems Project conducts research on the safety and performance of multiple collaborative robots using a mobile platform, an AGV with an onboard manipulator. Industrial manipulator [7, 8] and AGV [9] safety standards mandate failsafe control of these devices, but there is little overlap between the standards and gaps result [10] when the two systems are combined into mobile manipulators. One such gap is in competing control decisions based on obstacle detection from the AGV and/or industrial manipulator, as well as other aspects including AGV and robot position and speed. For example, if the manipulator senses a potential collision with an obstacle, the AGV may not register that obstacle as a potential collision. Figure 1 (left) depicts one possible situation, and Figure 1 (right) shows the NIST mobile manipulator testbed used to explore the situation. The industrial manipulator and the AGV each have independent controllers with collaborative decisions to make so that appropriately safe movement proceeds. There are several ways to provide this decision-making control, including:

- Independent– each robot makes decisions to account for its own safe control regardless of the other robot;
- Master/Slave – one robot leads decision making for both robots;
- Fused – three alternatives for decision making:
  - Shared model (decision rules) – sequential and complementary state transition;
  - Implicit coordination – one robot attempts to coordinate its motions based on the observed actions of the other; and
  - Explicit coordination – two or more robots are commanded by a central controller, or exchange detailed information to provide clear instructions for where the robots should move.

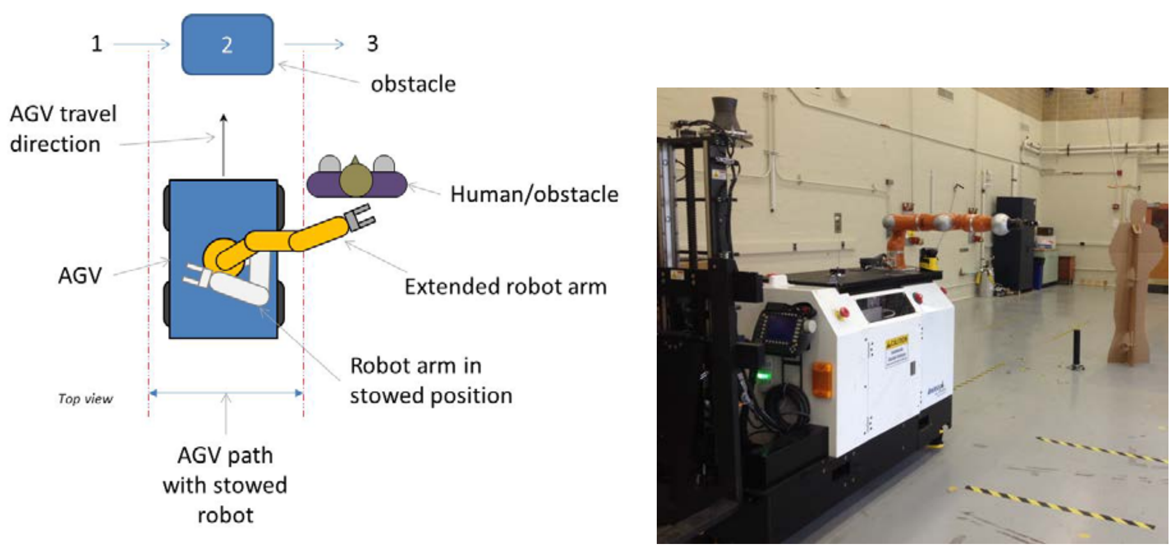

Figure 1 – Graphic (left) and photo (right) of a robot mounted onboard and collaborating with an AGV with a forklift for safe operation.

2. GAPS BETWEEN AGV AND ROBOT STANDARDS

The safe integration and operation of industrial manipulators and AGVs in industrial settings are ensured by means of national and international safety standards. These standards expound test methods and metrics to verify and validate the safe functionality of robotic systems and hazard avoidance measures. There are currently no international standards for the safety of AGVs, but most industrialized nations have their own national standards for AGV safety. In the U.S., the AGV safety is dictated by American National Standards Institute (ANSI)/Industrial Truck Safety Development Foundation (ITSDF) standard B56.5 [9]. Internationally, industrial manipulator safety is governed by means of the two parts of International Organization of Standardization (ISO) standard 10218 [7, 8]. These two parts outline the safety functions, features, design, and control of individual industrial manipulators and industrial-manipulator systems.

In 2012, the U.S. national standards committee on industrial robot safety, the ANSI and Robotics Industries Association (RIA) standard R15.06 [11] adopted ISO 10218 as the updated U.S. industrial robot standard. When taken separately, these national and international standards provide the basis for ensuring the safe integration and operation of their respective robotic technologies. However, when industrial manipulators and AGVs are physically and logically combined, the existing standards are insufficient for maintaining safety.

In a previous report [10], we outlined a number of likely scenarios for which the national and international safety standards either do not support or cannot be applied to mobile manipulators. Some of those scenarios are highlighted in Table 1. This paper is most interested in those stemming from the centralization of control. The control rules differ for AGVs and industrial manipulators for many situations. Depending on which rules are applied, the resulting behaviors of the resulting conjoined robot may be incompatible with the safety requirements of each component robot. On the other hand, if the industrial manipulator and the AGV maintain their separate controls, abiding by existing safety implementations may cause system conflicts that could potentially introduce new hazards if not properly accounted for during integration.

Table 1: Example operational conditions that have limited or no coverage in either the AGV (A) or industrial manipulator (R) safety standards using either a single- or dual-control mobile manipulator configuration. Conditions marked with "A/R" are covered by both the AGV and industrial manipulator standards, while cells marked with "--" are not covered by either.

		Moving AGV + Stationary Arm		Stationary AGV + Moving Arm		Moving AGV + Moving Arm	
		Single	Dual	Single	Dual	Single	Dual
a	Unexpected startup of industrial manipulator or AGV	A/R	A/R	A/R	A/R	A/R	A/R
b	Industrial manipulator/AGV hardware safety interlock	A/R	A/R	A/R	A/R	A/R	A/R
c	Human approach angle other than current direction of AGV travel, human is… …in industrial manipulator work volume, in AGV path …out of industrial manipulator work volume, in AGV path …in industrial manipulator work volume, out of AGV path	 A/R A R	 A/R A R	 A/R A R	 A/R A R	 A/R A R	 A/R A R
d	AGV position uncertainty	A[1]	A[1]	A[1]	A[1]	A[1]	A[1]
e	Industrial manipulator position uncertainty	R[2]	R[2]	R[2]	R[2]	R[2]	R[2]
f	Conflicting emergency stop situations	A	A	A	A	A	A
g	Industrial manipulator sensing within the restricted space	A	A	A/R[3]	A/R[3]	A	A
h	Mobile manipulator stability	A[4]	A[4]	A[4]	A[4]	A[4]	A[4]
i	Overhanging obstacle extends into industrial manipulator or AGV path	A[5]	A[5]	A[5]	A[5]	A[5]	A[5]
j	Reporting joint configuration of industrial manipulator	A/R	A	A/R	A	A/R	A
k	Industrial manipulator/AGV inhibiting motion of the other	A/R[6]	A	A/R[6]	A	A/R[6]	A
l	Planned/automatic restart from pause/stop	A/R	A	A/R	A	A/R	A
m	Sensing beyond vehicle path	A/R	R	A/R	R	A/R	R
n	Competing/incompatible safety protocols	A/R	--	A/R	--	A/R	--
o	Human carrying large load into AGV/manipulator path and vice versa	--	--	--	--	--	--
p	Velocity of any point greater than that of AGV/manipulator	Not Applicable		R		--	
q	Unplanned restart from pause/stop	A/R	--	A/R	--	A/R	--
r	Error recovery startup	R	--	R	--	R	--
s	AGV/manipulator software safety interlock	R	--	R	--	R	--
t	AGV/manipulator position/configuration update and verification	A/R	--	A/R	--	A/R	--
u	AGV/manipulator assumes master control during a pause event	A[7]	--	A[7]	--	A[7]	--

[1] ANSI/ITSDF B56.5 requires detection of obstacles only within the planned AGV path
[2] per ISO 9283 [12]
[3] ISO10218-2 requires sensing within a restricted, safeguarded spaces, possible only if the AGV is not moving
[4] Partial. Per ANSI/ITSDF B56.5, 4.2.5, 9.2.2: "Only stable or safely arranged loads shall be handled"
[5] ANSI/ITSDF B56.5 requires only standard test pieces to be detected within the contour area
[6] ANSI/ITSDF B56.5 and ISO 10218-2 each cover part of the motion inhibition requirements, neither covers both separately
[7] ANSI/ITSDF B56.5 is not specific to onboard equipment causing a fault

In certain circumstances, both the AGV and industrial manipulator standards provide requirements for handling potential hazards. For instance, both standards cover safety issues related to unexpected startups of the robots and hardware interlocks (items *a* and *b*, respectively, from Table 1). In other circumstances, such as positional uncertainty (items *d* and *e*), appropriate guidelines exist in one standard but not the other. There are still some scenarios, however, where gaps in the safety standards still exist. That is, there are potential hazard situations when neither the AGV nor industrial manipulator standards provide guidance. These situations represent the largest points of concern because it is not always clear what the integrated response to sensor and signal inputs will be. Applicable test methods must be defined to provide empirical evidence detailing the nature of those responses.

In a follow-up paper [13], we describe a number of evaluative measures that can be used to assess the performance of integrated mobile manipulator systems. One of those measures was designed to validate the expected functionality of an integrated mobile manipulator working in a safe, controlled manner. Throughout the tests we used to compute the measures, the person conducting the evaluation would be able to identify and remedy potential issues arising from the systems' integration and the improper handling of safety concerns. Admittedly, some of the test methods described in that report were *ad hoc*. Nevertheless, such tests are intended to provide bases for more stringent verification and validation methodologies as technologies mature, and industrial applications and interested standards bodies gain momentum.

3. COLLABORATIVE-ROBOT DECISION SHARING

For a dual-controller mobile manipulator system to be coordinated, context sensitive information must be exchanged. There are three possible levels of motion synchronization: base level, coordination level, and control level. These levels are summarized in Table 2.

Table 2: Summary of the three levels of synchronization possible for mobile manipulator safety and control

	Synchronization Level		
	Base	**Coordination**	**Control**
Simultaneous motions allowed?	No	Yes	Yes
Time synchronized?	No	No	Yes
Level of system access	None; basic digital I/O or integration into safety circuitry	High-level program access and digital/analog I/O	Real-time, low-level system access
Signal type/format	Digital validation signals, emergency stop and perimeter guard integration	Serial/socket communications and/or digital/analog inputs	Serial/socket/bus communications

The base level of synchronization represents a bare minimum of safe functionality and integration, and results in a mutually exclusive motion profile. Specifically, either the industrial manipulator or the AGV is allowed to move, but not both simultaneously. This level of synchronization also requires the integration of perimeter guard and emergency stop safety circuits. This ensures that when an event causes one robot platform to stop, the other stops at the same time. The signals necessary for the mutually exclusive motion synchronization consist only of digital inputs to indicate that one platform or the other has stopped. Such signals originate from sources external to the respective robot system, and can include beam breaks or contact switches that must be maintained. The base level of synchronization requires little onboard program logic in either the industrial manipulator or the AGV. Instead, enabling and execution of robot programs can be implemented using a programmable logic controller (PLC) to bridge the industrial manipulator and the AGV.

The coordination level of motion synchronization is necessary when the actions of one device influence the actions of the other. These actions require the synchronization of gross motions that are not time synchronized and not directly supportive of a common task – such as tracking the path of the AGV and onboard equipment in three-dimensional (3D) space. Exchanged signals are conveyed via serial or socket-based communications, or implemented using a combination of digital and analog inputs and outputs (I/O) associated with predetermined, high-level interpretations of the incoming signals. These signals include requests and acknowledgements for gross motions of the partner robot system, reports and verification of poses or configurations, and sensor feedback from onboard systems such as laser scanners, cameras, and force sensors. For the coordination level, high-level program access with a reasonable and guaranteed interface timer (e.g., > 10 Hz for the evaluation and execution of signals) is required for the sending, receipt, and interpretation of exchanged messages.

The control level of motion synchronization is required for the motions that must be time-synchronized to achieve the goals of a collaboratively shared task. Here, both robot systems move together as a single, fluid entity rather than as two coupled agents negotiating for control. These signals are integrated into the control of both robots in real time for both explicit and implicit motion coordination (closed-loop motion control). This requires fast (e.g., > 1 Khz), low-level access of the separate controllers to implement the time and spatial synchronization.

The three methods for decision making control described in Section 1 require different minimum synchronization levels for integration. Independent control can be implemented if only the base synchronization level is available. In contrast, the motion requirements of master/slave control require a minimum of high-level functionality be present at the coordination level. Similarly, while some functionality for fused control can be achieved at the coordination level of synchronization, any advanced, time-synchronized motions will require control level system access.

4. MOBILE MANIPULATOR TESTS

We conducted four tests to demonstrate Independent and Master/Slave safety control of the AGV/robot manipulator system. Figures 1 and 2 show the various configurations we used for those tests. A manipulator with its controller, a stow switch, and a beam break switch (see Figure 2) were mounted onboard an AGV. The stow switch was wired (a) into the AGV emergency stop circuit as a low level interrupter for Test 1, and (b) as a parallel input to the AGV controller inputs/outputs (I/O) circuit for Test 3. The beam break switch was wired to a manipulator controller input for Test 2.

When we conducted the tests for independent control, each robot made independent safety-related decisions, which we considered to be the default modus operandi. These safety-related decisions are clearly established by the manufacturers and clearly guided by existing safety standards [4] and [5]. As the Independent tests demonstrate, collaborative robots are defined only minimally in current safety standards; this limits their smooth interactions as they attempt to perform tasks efficiently and effectively.

Test 1 was an Independent test that demonstrated how onboard equipment, in this case a manipulator, could independently control an AGV. If the manipulator is expected to perform a task independently, the system must be configured so that the AGV remains stopped while the task is performed. For our experiment, this happens by first touching a stow switch to stop the AGV and then touching it again when the task is completed. The simple test was set up to allow the AGV to move from one point to another and to allow the manipulator to simultaneously move, after a short AGV start-moving delay, from the stow switch - effectively breaking the AGV emergency stop circuit and causing it to stop. When the manipulator was reconfigured to touch the stow switch, the emergency stop circuit was again repaired and the AGV continued on its programmed path. In this case, no verification or further information, other than the stow switch, was sent from the AGV to the manipulator or from the manipulator to the AGV.

Alternatively, Test 2 was an Independent test that demonstrated how an AGV could independently control an onboard manipulator when the AGV was configured as expected for the manipulator to be controlled. If the manipulator is told to perform a task independently, but the AGV is not stopped and located at the correct position - as measured by a beam break sensor- a misalignment occurs. The misalignment causes the robot to stop its current task and to stow. When the AGV is realigned, the manipulator can once again work on the given task. Again, no verification or further information, other than the beam break was misaligned, was provided to the robot.

Figure 2: Robot onboard an AGV with low level safety control verification (a) stow switch used for Test 1 and (b) beam break switch used for Test 2.

Test 3 and Test 4 demonstrated Master/Slave collaborative robot safety performance where one robot leads decision making for both robots. The test scenarios focused on smart, collaborative robot performance, which requires that both robots can move simultaneously to perform tasks. Examples include: a manipulator attempting to access points that it cannot reach from one fixed robot base location or an AGV moving through a hazard (e.g., restricted space) area where onboard equipment must be reconfigured to fit both robots through the space. Mechanisms, such as onboard or off-board perimeter safeguarding, are required to initiate a safety response. For the tests, the AGV laser bumper safety sensors were used to inform the AGV of obstacles and the manipulator included a laser safety sensor mounted at its base onboard the AGV to inform the manipulator of obstacles. Low level controls, such as those demonstrated in Tests 1 and 2, can also provide hardened verification or redundancies of a stopped and properly configured robot to support the Master/Slave performance. We used the manipulator stow pushbutton as a verification to the manipulator that it was stowed. Table 3 shows the various I/O sent or received between the AGV and the manipulator.

Table 3 – I/O between the AGV and the manipulator. Variables labeled 'robot' = manipulator.

Outputs from AGV to Robot	*Definitions*
moRobotStowRequest	AGV requests the robot to stow
moRobotCanMove	AGV informs the robot it can move
moAGVStopped	AGV informs the robot it has stopped

Inputs to AGV from Robot	
miAckRobotStowed	Robot acknowledges to the AGV it has stowed
miRobotRequestAGVStop	Robot requests the AGV to stop

Inputs to Robot from Sensors	
RobotAreaClear	Robot acknowledge that its workvolume is clear
RobotStowed	Robot acknowledgement that it has stowed

Test 3 was a Master/Slave collaborative robot experiment that demonstrated the AGV as the master and the manipulator as the slave. The test required the following components be added to the existing AGV software: laser safety bumper software to include idle status (i.e., ready to move), robot stow status, and wait to clear status (i.e., safety bumper laser detection and ranging sensors detect or do not detect an obstacle). Manipulator software was programmed to accept inputs or provide outputs as shown in Table 3 and to act as each variable is defined. Test 3 procedure was:

- the AGV moved until it detected an obstacle in the path, the AGV stopped and sent a stop to the manipulator,
- the manipulator moved to the stow position and was prevented from moving until the moRobotCanMove once again sent to the manipulator from the AGV,
- verification and validation that the stop request to the AGV and to the robot were working and that the robot moved to a safe position (stow) prior to continuing operation.

Handshaking from the AGV to the manipulator is further detailed in Table 4.

Table 4 – Test 3 case scenario, variables and handshaking verification.

case scenario	variable	logical state
AGV idle	moRobotStowRequest	0
	moRobotCanMove	1
if slow or stop fields are interrupted, send →	moRobotStowRequest	1
(i.e., obstacle is in AGV fields)	moRobotCanMove	0
and go to 'stow request'		
stow request	moRobotStowRequest	1
	moRobotCanMove	0
if robot stow is verified, receive →	miAckRobotStowed	1
(i.e., stow button is pushed and sends a high to AGV)	moRobotStowRequest	0
and go to 'wait to clear'		
wait to clear	moRobotStowRequest	0
	moRobotCanMove	0
if no obstacle in AGV fields, send →	moRobotCanMove	1
and go to 'AGV idle'		

Test 4 was a Master/Slave collaborative robot experiment that demonstrated the manipulator as the master and the AGV as the slave. The test required that AGV software components be changed as follows: variable sSoftstop changed causing a variable deceleration, dependent upon AGV velocity, so that the AGV does not suddenly stop as in an emergency stop condition; the RobotRequestAGVStop input variable is changed and sends an AGVStopped acknowledgement to the robot. The laser safety sensor for the manipulator was used as the obstacle detect input to the manipulator. Test 4 procedure was:

- the manipulator moved until it detected an obstacle in its horizontal work volume boundary as set in the laser safety sensor. The manipulator stopped and also sent a sSoftstop to the AGV,
- the manipulator moved to the stow position until the obstacle was cleared,
- when the manipulator safety sensor was clear, the AGV no longer received a request to stop by the manipulator,
- verification and validation that the stop request to the AGV and to the robot were working

Handshaking from the manipulator to the robot is further detailed in Table 5.

Table 5 – Test 4 case scenario, variables and handshaking verification.

case scenario	variable	logical state
AGV idle (stopped or moving) *don't softstop AGV*	*sSoftStop*	0
if robot wants to move, AGV receives →	miRobotRequestAGVStop	1
bring AGV to a softstop	*sSoftStop*	1
and go to 'stopped?'		
is AGV stopped? if AGV is stopped, then send →	moAGVStopped	1
and go to 'wait to clear'		
wait to clear AGV still stopped	*sSoftStop*	1
if robot isn't asking AGV to stop, AGV receives →	miRobotRequestAGVStop	0
clear the softstop	*sSoftStop*	0
go to 'robot idle'		

5. PERFORMANCE TEST RESULTS

Independent tests 1 and 2 performed as expected verifying that hardware interlocks of stow and beam break switches can provide a mobile manipulator with the level of safety representative of typical machine interlocks. However, also as expected, one robot was 'locked out' of performing simultaneous tasks by the other robot.

Master/Slave tests 3 and 4 also performed as expected, although it is understood that the manufacturing industry and safety standards may not be as receptive to software interlocks as hardware interlocks. However, future smart manufacturing robotic systems may desire this capability. Test 3 and Test 4 demonstrated clear, sequential command and status transfer from one robot to the other. Simultaneous robot motions with demonstrated obstacle detection and robot reaction occurred. The example in Figure 3 shows the manipulator stowed after the AGV detected an obstacle (safety cone) in its path.

Timing and safety field range settings were viewed as possible instances where Test 4 sSoftstop of the AGV may be too slow to react to possible hazards. For example, when the AGV is commanded by the manipulator to stop, AGV deceleration combined with manipulator safety sensor obstacle detect may be too slow or the safety field set too short to ensure contact between the robot and obstacle is prevented. Similarly, the Test 3 AGV safety sensor and manipulator stow speed may require adjustments to minimize risk of manipulator contact with obstacles. Tests 1 through 4 were each performed approximately five times and were intended to demonstrate feasibility of real, commercial-off-the-shelf robot systems to perform coordinated control. Statistical data from more comprehensive tests could provide increased performance knowledge of these robot systems and uncover further robot coordination issues.

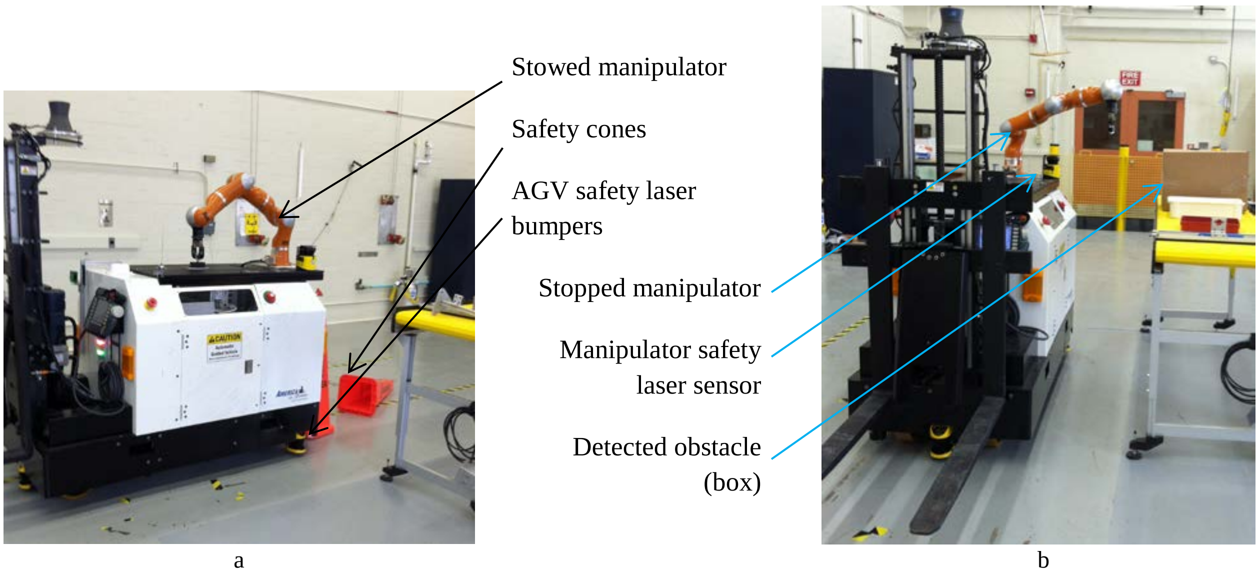

Figure 3 – (a) Test 3 result of an obstacle (safety cone) detected by the AGV and the manipulator stowed after the AGV informed it to do so, (b) Test 4 result showing an obstacle (box) detected by the manipulator safety laser sensor, the manipulator being stowed, and the AGV stopped after the manipulator informed the AGV to do so.

6. FUTURE RESEARCH PLAN

Future testing research will focus on fused control between robots. Fused control incorporates three alternatives for decision making: shared model, implicit coordination, or explicit coordination. Shared model (decision rules) applies predefined decision rules to achieve adaptive collaborative control. High-level tasks may be set by an operator or another high-level controller. The shared model approach allows for lower-level, independent, robot decisions that may be more adaptive or more flexible if the robot controller has such a capability. A test, therefore, might include a high-level controller defining a task that requires each robot to have low-level shared control and independent control simultaneously.

In an example depicted in Figure 4, a mobile manipulator is commanded to retrieve an object from fixture 1 and move it to fixture 2. This requires the AGV to move from one to the other. Even though the fixtures are outside of the AGV path, the manipulator and AGV have predetermined locations from which access is possible. In the example scenario, shared control is needed to accomplish the task; but independent control is needed for the decisions made by each robot. For example, if the AGV controller detects an obstacle in its path, it causes the AGV to stop and inform the manipulator robot to stop and perhaps stow. The human then removes the obstacle, at which time the AGV controller allows it to move. The AGV controller then informs the manipulator controller that it is ok to move. However, the manipulator controller informs the AGV controller that another obstacle (i.e., human) is still preventing it from moving. The manipulator then directs the AGV to remain stopped until the human is out of the manipulator's work space. When the human is outside the manipulator's work space, then both the AGV and the manipulator can continue with the assigned task.

For implicit coordination, each robot attempts to coordinate its motions based on observed actions of the other robot(s). As an example, we again use the previous obstacle scenario shown in Figure 4. Note that the AGV path obstacle is also detected by the manipulator. In implicit coordination, the manipulator can begin to preplan possible actions should the AGV be allowed to avoid the obstacle instead of waiting for the human to clear it from the path. Similarly, the AGV also detects the human and can take associated precautions.

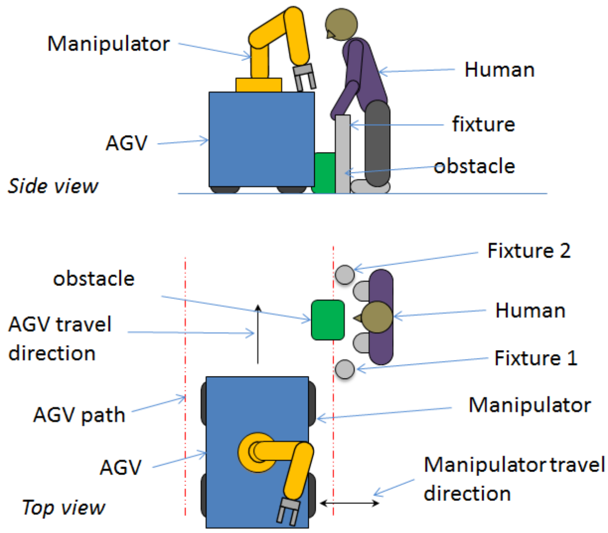

Figure 4 – Graphic showing side and top views of a collaborative robot scenario where a mobile manipulator is accessing two different fixtures while unaware that a human entered the zone to remove an obstacle from the AGV path.

For explicit coordination, collaborative robots are commanded by a central controller. Therefore, all information exchanges occur between the robots and central controller only. Continuing with the example in Figure 4, each time an obstacle is detected, that information is passed to the central controller which provides detailed and sequential information to each robot. For example, upon obstacle detection and removal by the human, the central controller commands both the AGV and manipulator to remain stopped until the human is out of the work space.

Coordination problems can still arise regardless of the coordinated control concepts presented. Consider the following example, in which <u>all information sharing passes through the central controller</u> and not directly between robots.

- The AGV and manipulator get a command to move to a location.
- En route, an object is encountered in the AGV's path
- The AGV receives the manipulator configuration, including the planned manipulator trajectory and recognizes that there is a potential collision between the manipulator and a human.
- The AGV informs the manipulator to stow
- Negotiation option #1:
    - The manipulator refuses to stow (e.g., it cannot achieve its transition task while in a stowed configuration)
    - The manipulator tells the AGV to detour along a specific path (e.g., "pass on the right")
    - The AGV plots a new path around the collision and informs the manipulator of the new trajectory
- Negotiation option #2:
    - The manipulator agrees to stow, and during the stow motion continuously sends "manipulator moving" to the AGV
    - Simultaneously, the AGV continuously sends "AGV moving" to the manipulator
    - The AGV encounters an identified collision event and is still getting "robot moving" messages; The AGV decides that the robot may still be in a collision state
    - The AGV begins to slow, informing the manipulator that it is slowing.
    - The manipulator finishes its stow operation and informs the AGV that it is not moving any more
    - The AGV resumes speed and passes the collision event
    - The AGV informs the manipulator that the collision is passed, and that the manipulator can move back to its original configuration

7. CONCLUSIONS

This paper described three coordinated control methods to enact safe operations: Independent, Master/Slave, and Fused. Tests were designed and performed to measure Independent and Master/Slave coordinated control method performance. Independent control is essentially part of the ANSI/ITSDF B56.5 safety standard where all onboard AGV equipment must interlock control with the AGV for safety and reliability. However, as smart manufacturing robotics begins to allow more flexible environments with increased human interaction, higher level coordinated control implementations between robots will become necessary. Therefore, more complex Master/Slave and Fused coordination control methods will be used to improve efficiencies. Master/Slave tests were presented demonstrating that timing and safety sensor field and range settings could be potential issues causing slow robot reactions and raising hazard risks. An example test scenario was presented for planned follow-on research to measure performance of Shared model, Implicit coordination, and Explicit coordination control methods.

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