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MAR-CPS: Measurable Augmented Reality for Prototyping Cyber-Physical Systems

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Cyber-Physical Systems (CPSs) refer to engineering systems that rely on the integration of physical systems with control, computation, and communication technologies. Autonomous vehicles are instances of CPSs that are rapidly growing with applications in many domains. Due to the integration of physical system with computational sensing, planning, and learning in CPSs, hardware-in-the-loop experiments are an essential step for transitioning from simulations to real-world experiments. This paper proposes an architecture for rapid prototyping of CPSs that has been developed in the Aerospace Controls Laboratory at the Massachusetts Institute of Technology. This system, referred to as MAR-CPS (Measurable Augmented Reality for Prototyping Cyber-Physical Systems), includes physical vehicles and sensors, a motion capture technology, a projection system, and a communication network. The role of the projection system is to augment a physical laboratory space with 1) autonomous vehicles' beliefs and 2) a simulated mission environment, which in turn will be measured by physical sensors on the vehicles. The main focus of this method is on rapid design of planning, perception, and learning algorithms for autonomous single-agent or multi-agent systems. Moreover, the proposed architecture allows researchers to project a simulated counterpart of outdoor environments in a controlled, indoor space, which can be crucial when testing in outdoor environments is disfavored due to safety, regulatory, or monetary concerns. We discuss the issues related to the design and implementation of MAR-CPS and demonstrate its real-time behavior in a variety of problems in autonomy, such as motion planning, multi-robot coordination, and learning spatio-temporal fields.

I. Introduction

Hardware-in-the-loop experiments are an essential step for transitioning implementation of planning and learning algorithms from simulations to physical systems. They are not only important for verification of an algorithm's performance in real-time, but also for conveying behavioral characteristics of algorithms

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to researchers and spectators. Additionally, they allow determination of an algorithm's robustness to uncontrollable factors such as environmental uncertainty and sensor noise, which need to be verified before deployment into a real-world setting. However, operation of experimental hardware in an outdoor environments may be disfavored due to safety or regulatory concerns. For instance, recent Federal Aviation Administration regulations have limited the testing and flight of Unmanned Aircraft Systems (UAS) in outdoor spaces, and have completely barred private institutions from doing so [1]. This paper details an indoor, experimental architecture which allows controlled testing of planning and learning algorithms in a simulated outdoor environment. The proposed architecture combines motion capture technology with edge-blended multi-projection displays and enables rapid prototyping of Cyber-Physical Systems (CPSs), with a focus on designing planning, perception, and learning algorithms for autonomous single-robot or multi-robot systems.

During execution of planning and learning algorithms, numerous latent variables such as probability distributions over system state, predicted agent trajectories, and transition probabilities are manipulated. Though hardware experiments allow spectators to observe performance of such algorithms in the real world, it is difficult to simultaneously convey latent information alongside physical platforms. Apparent performance of algorithms relying on complex background processes can, therefore, suffer due to this complexity not being appropriately conveyed to spectators.

In certain scenarios, once experimental data is gathered, latent information can be visualized through simulation software. However, it may be difficult for spectators to synchronously monitor behavior in the simulator and on the physical platform, especially in the case of real-time algorithms. It is much more beneficial to augment the experiment area with real-time visualization of this data, allowing direct perception of the progress of the planning/learning algorithm.

The ancestor of MAR-CPS, referred to as RAVEN (Real-time indoor Autonomous Vehicle test ENvironment) was designed to facilitate rapid prototyping of autonomous vehicle systems through modular mission, task, and vehicle components [2]. This inherent flexibility in the architecture allows system managers to easily change mission specifications such as high-level goals or the number/type of vehicles involved in tasks. Our extension of RAVEN to include augmented reality maintains this modularity. Specifically, software and hardware required for the projection architecture can be fully decoupled from the rest of the mission, allowing experiments to be conducted even when the projection system is offline.

The primary contribution of this work is an augmented reality system architecture which can be implemented in other research laboratories, allowing a transformation of an indoor spaces into interactive outdoor world environments.

II. Related Work

Various prototyping environments for CPSs have been developed in the past [2–6], including both in hardware and in simulation. Addition of augmented visualization capabilities to such platforms has seen recent interest. Boston University recently investigated display of dynamically changing events using projectors for hardware experiments involving quadcopters [7]. Specifically, they indicate reward and damage information for quadcopters involved in an aerial surveillance mission, although simulation of complex mission scenarios or measurement of the augmented environment using onboard sensors is not demonstrated.

Investigation of augmented reality for multi-robot mission scenarios has also been conducted [8], including applications in pedestrian perception and tracking of swarm robotics. However, their applications are limited to display of this information in software only, and integration of the data into a physical laboratory space has not been conducted yet.

Onboard projection systems have also been investigated for human-robot interaction situations [9], with applications in robot training demonstrated.

Due to the recent affordability of virtual reality headsets, such as the Oculus VR system [10], their usage in a CPS-prototyping setting was initially considered. Usage of virtual reality head-mounted displays to superimpose mission data over a live camera feed has previously been investigated [11], with applications to intruder monitoring in swarm robotics demonstrated. However, for laboratories involving large teams of researchers, or for demonstrations involving large groups of spectators, this idea may be infeasible as
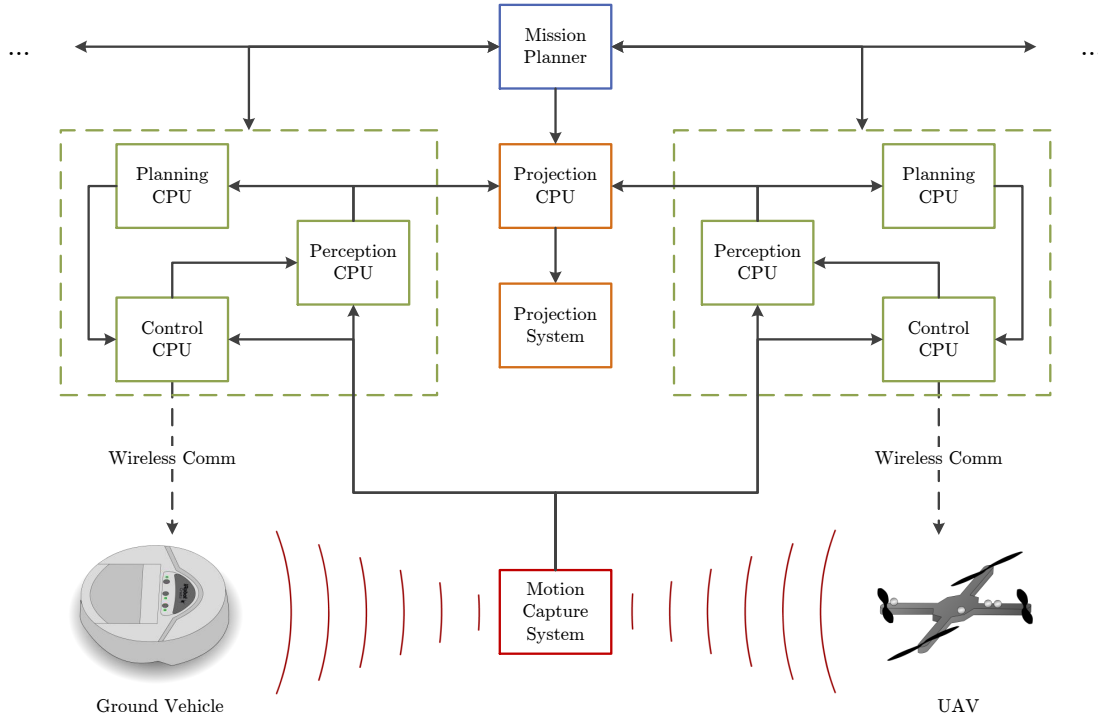
Figure 1: Architecture overview for MAR-CPS, for a mission involving both ground and air vehicles.

a virtual reality headset and its supporting infrastructure need to be prepared for each human observer. Additionally, information displayed in a virtual reality headset is not measurable using onboard sensors on a vehicle, whereas projected images are physically present in a lab and can be directly measured.

Our system leverages the emergence of motion capture technology usage in indoor testing of CPSs, and presents a platform for prototyping vehicles in a simulated outdoor environment. Additionally, we extend previous work by demonstrating that measurement of projected environments can be a useful tool for obtaining sensory data in situations where outdoor testing is infeasible.

III.   System Architecture

Fig. 1 illustrates the system architecture. The system has several main components: i) a high-level mission manager, ii) autonomous vehicles (each with access to a planning, control, and perception CPU) equipped with on-board sensors, iii) motion capture system, and iv) projection system.

The central mission planner coordinates high-level tasks for the vehicles, given the mission objective. For instance, in a multi-robot package delivery scenario, the central planner assigns packages and delivery destinations to individual vehicles. This architecture can be extended to decentralized systems where each vehicle chooses its own tasks based on local observations.

Each vehicle communicates with a designated CPU for planning, perception, and (low-level) control. Given a task, the planning CPU defines a valid trajectory for the vehicle. The trajectory is relayed to a control CPU, which defines low-level control inputs to the vehicle using feedback from the motion capture system. Note that the planning CPU also has knowledge of the controllability of the vehicle in question, but its role can be combined with the control CPU if desired.

The vehicle can simultaneously perceive or measure the projected virtual environment and convert these observations to useful features of the environment using its perception CPU. For instance, the perception

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CPU can process still images from a camera sensor to find objects of interest, which can then be tracked using the planning and control CPUs. The perception CPU has the additional task of performing state estimation using the motion capture data.

The capability to perceive the projected (augmented reality) environment allows replication of outdoor test environments in a controlled, indoor space. Sensor systems used in outdoor environments can similarly be used in MAR-CPS to obtain noisy measurements, allowing robustification against stochasticity. Additionally, the modular architecture of MAR-CPS allows tests in a variety of simulated environments to be conducted with low overhead.

III.A. Hardware

Fig. 2 illustrates a hardware overview for MAR-CPS. The visualization system is implemented in MIT Aerospace Controls Laboratory's RAVEN [2] indoor flight testbed. This system utilizes 18 Vicon T-Series motion-capture cameras allowing tracking of heterogeneous teams of autonomous vehicles [12]. A unique pattern of reflective motion capture markers is affixed to each vehicle, allowing the motion capture system to determine the position and orientation of the vehicles .
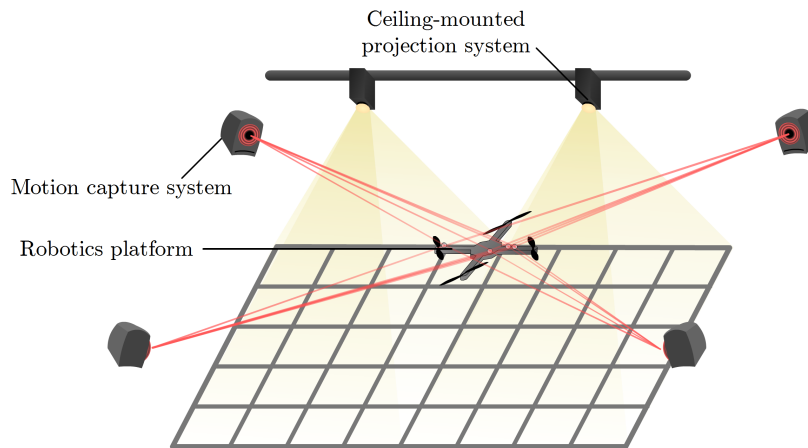

Figure 2: Hardware overview for MAR-CPS.

State and latent information for the vehicles are published to the laboratory network using Robot Operating System (ROS) [13], allowing feedback control of the vehicles, as well as a computer dedicated to visualization-rendering to package this information in an intuitive format for researchers. The visualization is then projected onto the experiment area using 6 ceiling-mounted Sony VPL-FHZ55 ground projectors, with latent data animations and physical systems being run synchronously. This allows designers and spectators to observe hardware while simultaneously gaining an intuitive understanding of underlying decisions made by planning and learning algorithms.

A primary challenge in implementing this system was to ensure that the footprint of the experiment testbed would not be downsized. The 1200-plus square foot RAVEN laboratory space is used for experiments involving a variety of ground and air vehicles, therefore restricting its size to be equal to the footprint of a single projector was infeasible. Two solutions are presented for this. First, the projected area can be treated as a window into the belief space. Though the hardware itself may run in a larger physical space, visualization can be presented only for specific sub-regions of this space. This window gives spectators an understanding of the decision-making scheme used by the algorithm, allowing them to extend its behavior to regions where no visualization is presented. Second, the projected area is not necessarily constrained to the size of a single projector. Instead, multiple projectors are combined in order to increase the overall

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visualization footprint. Details regarding seamless calibration of a multi-projector system are presented in the next subsection.

Additional hardware can be appended to MAR-CPS in order to simulate outdoor environments more realistically.

III.B. Multi-Projection System Calibration

MAR-CPS utilizes a multi-projector system for visualization of information in the physical lab space. This presents challenges due to misalignment in the projectors' mountings, causing affine warping and distortions in the visualizations. Additionally, it is infeasible to permanently align the edges of the projected images in hardware, due to ground vibrations moving the projections over time, resulting in overlapping and/or gaps in the images.

To counter this, a software calibration scheme was implemented in collaboration with Scalable Display Technologies, a company specializing in multi-projector displays [14]. Driver-level changes on a computer running NVIDIA Mosaic-capable K5000 graphics cards allow edge-blending of projector displays, as well as de-warping of images in the lab environment. The end result is a seamlessly blended projection region with the majority of affine distortions removed.

Additional calibration is required for aligning the motion capture coordinate system with the visualization coordinate system, which is necessary for projection of real-time markers at the vehicles' positions. This calibration is non-trivial if the projection footprint is non-rectangular. In this case, a piecewise linear transformation can be utilized, due to relative ease of implementation as well as low computational overhead.

IV. Technical Features

Our system introduces a number of features which augment prototyping of autonomous systems in traditional laboratory spaces, as well as debugging and demonstration of planning and learning algorithms in real-time. These features are outlined in the following sections.

IV.A. Rapid Prototyping in Simulated Environments

The modular architecture of MAR-CPS is focused on minimization of logistics for autonomous vehicle research labs, allowing new vehicles and software capabilities to be added on-the-fly. Additionally, MAR-CPS provides visual awareness of both high and low-level information from both software and hardware platforms, making it an efficient testbed for rapid prototyping of autonomous vehicles. Additionally, in some usage scenarios, its implementation can be designed to be disjoint from experiments, allowing it to essentially be "turned off" without affecting vehicle behavior or performance of the experiments conducted.

Traditionally, testing an algorithm's performance in simulation and on physical systems has been disjoint. A typical framework for development of algorithms for autonomous vehicles involves initial experimentation in simulation, and a subsequent transfer to physical platforms (either in an indoor or outdoor environment). This transfer introduces problems such as discrepancies between models used in simulation and real-world models (of sensors, actuators, and environment), including miscalibrations. In particular these discrepancies in complex physical systems consisting of several interacting vehicles can make it very difficult to understand the behavior of algorithms or root causes of performance problems.

Traditional debugging schemes for such scenarios are iterative, requiring update of software, verification in simulation, and re-testing in hardware [15]. Specifically, debugging of software can require an understanding of low-level information while the experiment is being conducted, a process which can be time-exhaustive. MAR-CPS improves this by allowing display of such information in real-time. For instance, information regarding the location and velocity of vehicles can be visually shown next to them, allowing immediate identification of discrepancies between hardware sensors and software variables.

MAR-CPS is a platform designed for transformation of indoor laboratories into controlled simulations of outdoor environments in which experiments involving autonomous vehicles can be conducted prior to real-world deployment. This provides researchers an inexpensive pathway to field testing, which is distinct

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from traditional testing in simulations or indoor environments. Specifically, visual presence of obstacles, environmental conditions such as varying terrain type or wind velocity vector fields, and presence of restricted regions in a mission scenario can be indicated using MAR-CPS. For instance, Fig. 6 indicates trajectories as well as detected obstacles in a self-driving vehicle setting.

Additionally, vehicles used in MAR-CPS are not subject to wear-and-tear or unforeseen environmental factors that may damage them in a field test, leading to increased lifespans and minimization of effort spent by researchers on re-calibration or troubleshooting of hardware. Debugging of software issues in the simulated MAR-CPS environment is also eased, as full access to laboratory resources (which may be too costly or difficult to transport outdoors) is maintained.

Finally, in situations where physical vehicles are expensive, use of real-time projection in MAR-CPS allows integration of virtual vehicles in experiments. Physical and virtual vehicle interactions can be modeled in software, allowing inexpensive testing of complex, multi-agent mission scenarios. Section V.B presents an example domain with interacting virtual and physical agents.

IV.B. Display of Latent Information and Uncertainty

Application of planning and learning algorithms in real-world settings often requires handling of stochasticity in the environment. In such scenarios, each vehicle constructs a "belief" or probability distribution over the state of the world, using which it makes decisions regarding its next best action. Decisions made by planning algorithms may be counter-intuitive to human observers if a thorough understanding of a vehicle's perception of the environment is not conveyed.

Visualization of such information, specifically uncertainty levels in a vehicle's perceived state, is very useful in aiding researchers' understanding of algorithms. In the past, conveyance of this information in real-time has been difficult. Our solution uses ceiling-mounted projectors to show latent information about an autonomous agent, such as its perception of its own location, nearby obstacles, future trajectories, failure states, battery levels, and communication links with other team-mates.

IV.C. Measurable Augmented Reality:
Perception and Interaction in Simulated Environments

The quality of outdoor environment simulations is heightened by enabling perception of the projected imagery, closing the loop on the simulation architecture. More specifically, the combination of a projected simulated environment and sensors observing it creates a lab environment which is essentially a replacement for the outdoor world. Additionally, since MAR-CPS utilizes real-time projections in the laboratory space, simultaneous perception of physical as well as virtual agents and environmental features is possible. Section V.A explores an example application of this.

IV.D. Communication and Teaching Tool for Spectators

Conveying valuable information about autonomous vehicle algorithms is not only useful for researchers, but for spectators outside the research field as well. In some scenarios, even high-level descriptions of algorithms may prove difficult for spectators to understand. Though display of visual information or explanatory animations on a computer monitor may be effective, it can also detract from the experience of spectators as they must divide their attention between computer monitors and physical experiments.

Our solution is capable of showing latent or meta-information during demonstrations to spectators, which can be especially useful for transferring an intuitive understanding of the specific topic of research or specific mission scenarios. For instance, information regarding a given vehicle's overall objective, or messages declaring each vehicle's current task can be projected in the MAR-CPS environment.

IV.E. Vehicle Safety

MAR-CPS introduces useful safety features for testing autonomous vehicles, and can aid compliance to regulatory restrictions placed on research institutions.

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Figure 3: Vehicle health monitoring messages, such as damage of actuators or physical systems, can be displayed in real-time within MAR-CPS.

In scenarios where interaction of humans and autonomous hardware is dangerous (e.g., flight of large quadcopters in an enclosed environment), physical barriers provide a means of protection for operators and spectators. However, minimization of vehicle crashes and collisions due to software or hardware failures is also desirable. Though planned vehicle trajectories and health states [16] of vehicles can be displayed on a computer monitor, it may be difficult for researchers to monitor such information while simultaneously observing the vehicles themselves. Using MAR-CPS, the above information can be projected directly on the vehicle testbed, allowing researchers to observe and even predict dangerous behavior and react accordingly with faster response-time. Fig. 3 illustrates a scenario where a vehicle undergoes actuator damage and must leave the mission premise until it is repaired. Using MAR-CPS, spectators gain an understanding of such events without need for additional explanation.

IV.F. Regulations

In some scenarios, experiments involving autonomous vehicles cannot be conducted in a public setting, due to regulatory restrictions. For instance, the FAA recently limited tests of UAS by public institutions, and completely barred private institutions from doing so [1]. However, using MAR-CPS, institutions can conduct similar tests in a private, indoor setting without violating regulations.

V.   Applications

MAR-CPS was designed to be generalized enough such that it could be applied to a variety of research topics and experiments, such that it can be the standardized testing and prototyping environment for CPSs. Numerous experiments running autonomous teams of ground and air vehicles have already been conducted in MAR-CPS. The developed system has been tested in several different scenarios, such as forest-fire management (see Fig. **??**) and multi-agent intruder monitoring (see Fig. 5). In each case, the projector visualization is used to improve understanding of the vehicles' behaviors using meta-data such as vehicle position, health state, and viability of future actions.

V.A. Measurable Augmented Reality: Forest Fire Management Application

Our system enables the capability to construct dynamic mission environments, visualize them in a laboratory, use onboard sensors for perception of environment features, and allow testing and validation of complex planning algorithms.

The above capabilities were demonstrated in a heterogeneous multi-agent learning setting, with an application to forest fire management [17]. In this work, a discretized 12×30 static forest environment consisting of varying terrain and vegetation types (e.g., trees, bushes, rocks, etc.) was constructed and projected in MAR-CPS. Seed fires of varying intensities were initiated on the terrain, with a fire propagation model used for dynamically updating the intensities and distribution over the terrain. A quadcopter used an onboard camera (Sony 700 TVL FPV Ultra Low Light Mini Camera) to wirelessly transmit images to a perception CPU, which created a segmented panorama of the complete forest environment. Fig. ?? shows a perspective view of the MAR-CPS environment, as well as associated image captures obtained from the quadcopter.
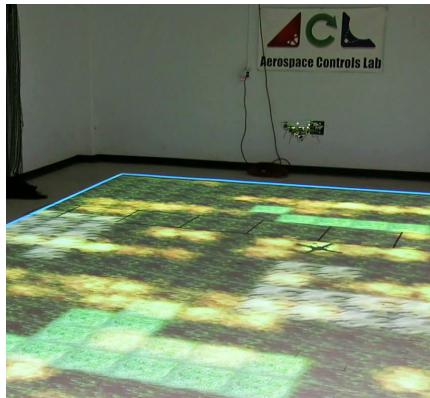
(a) Quadcopter fire fighting demonstration, perspective view.

(b) Quadcopter fire fighting demonstration, on-board camera view.

Hue-saturation values of the images were used for classification of fire intensity values throughout the discretized environment, resulting in an intensity matrix. Repeated applications of this process produced spatio-temporally varying intensity matrices, from which state transitions of fire intensity distributions were derived. This information was then utilized for accurate prediction of future fire propagation, allowing targeting of fire fighting efforts on more constructive regions of the environment.

This experiment highlights the use of MAR-CPS to create dynamic counterparts of real-world situations in an augmented reality environment, and use noisy measurement systems to predict real-life effectiveness of CPSs prior to deployment.

V.B. Planning for Large-Scale Multi-agent Problems

Due to its modular nature, MAR-CPS can be utilized in large-scale multi-agent planning problems. A recent application is intruder monitoring using a team of quadcopters [18]. In this problem, a team of autonomous ground vehicles attempts to reach a goal location in a discretized world while a competing team of quadcopters attempts to push or "herd" them away. Fig. 5 illustrates the domain (note that visualizations in the figure were projected in real-time in the laboratory space, and no computer post-processing was done on the images).

In this problem domain, the quadcopters solve a planning problem in which they first locate ground vehicles using a simulated radar system, utilize the stochastic state transition model to predict each ground vehicle's most likely next state, and use this information to choose which ground vehicles to focus their efforts on. The quadcopters can herd ground agents more effectively if they work in teams, and can make decisions regarding health management (such as refueling or requests for repair).

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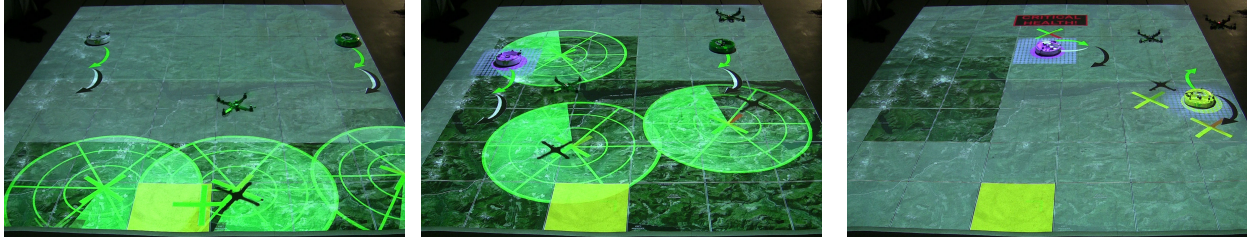
(a) Initiation of planning problem, with quadcopters using radar surveillance to detect ground vehicles.

(b) Detection of a ground vehicle by the quadcopter in the top left corner of the image.

(c) Quadcopters can work cooperatively (right) or individually (top) to herd away ground vehicles.

Figure 5: The multi-agent intruder monitoring mission with ground robots as intruders and quadcopters as the monitoring agents.

MAR-CPS is used as a visualization platform in this application. Satellite imagery is projected on the laboratory space, with foggy regions representing areas which have not been explored by quadcopters. A yellow grid square represents the goal destination of the ground vehicles (see Fig. 5a). Information about each vehicle's current task is provided through color-coding of their shadows, and specialized tasks such as radar surveillance have specifically-designed animations (Fig. 5a). As ground vehicles are detected by quadcopters, a GPS beaconing animation is overlaid on them (Fig. 5b).

The effectiveness of the quadcopters' planning algorithm is also indicated in real-time using MAR-CPS. As Fig. 5c illustrates, green arrows protruding from each ground vehicle indicate their most likely next state, while black arrows indicate their most likely next-next state had the quadcopters not been there. Likewise, white arrows indicate their next-next most likely state given the quadcopters' current positions (Fig. 5c). Transition arrows for the ground vehicles are updated in real-time, giving researchers and spectators an immediate and intuitive understanding of the impact of each quadcopter's position on the overall objective of keeping the ground vehicles away from their target destination.

V.C. Motion Planning Under Uncertainty

Robot motion planning is the problem of driving a moving robot from a start location to a goal location. In real-world applications, often a robot's motion and its sensory measurements are subject to noise. To plan motions for a robot under uncertainty, one needs to infer the current configuration of the robot based on the noisy measurements. The result of such an inference is a probability distribution over all possible configurations of the robot, that is referred to as "belief" [19]. Belief is not a tangible or physical concept and it only exists in the robot's mind. With MAR-CPS, these probability distributions can be projected on the physical environment alongside the robots. Moreover, the "intent" of the robot, e.g., the trajectory it decides to follow or the task it aims to complete, can be projected to the physical environment.

Luders et al [20] demonstrate the usage of MAR-CPS on motion planning under uncertainty. Fig. 6 includes a few snapshots of this demonstration. A chance-constrained rapidly randomized tree (CC-RRT) method is utilized to plan the robot's motion from its current location to goal (shown in yellow) in the presence of moving obstacles (people or smaller robots, i.e., iRobot Creates). The robot's perception of these moving/static obstacles is projected onto the ground in purple. The generated tree for planning is also projected in green, where the best trajectory is highlighted. This application highlights usage of MAR-CPS in an autonomous driving scenario, where visualization of planned paths can be highly useful for debugging or calibration purposes.

V.D. Human-Robot Interactivity

Taking advantage of the motion capture system utilized in MAR-CPS, human-robot interactivity can also be demonstrated. Specifically, tracking sensors can be placed on a human to allow interaction with autonomous

vehicles from a safe distance. Additionally, props can be used for representation of objects within the simulated world. For instance, one demonstration involves a quadcopter landing due to a simulated onboard fire (see Fig. 7a), and a human operator subsequently using a water spout prop to quench the vehicle (see Fig. 7b). Simultaneously, the projection system in MAR-CPS displays both fire and water animations using a particle system, conveying the impact of the interactive process to spectators. Such examples of human-robot interactivity allow demonstrations of scenarios which would otherwise not be possible to perform in an enclosed laboratory space.

V.E. Multi-agent Telecommunication Links

A mission scenario involving visualization of communication links between agents in a multi-agent setting has been developed (see Fig. 8a). In this experiment, one ground vehicle (the "leader") contains a communications beacon that can be used to assign tasks to a fellow agent (a "follower"). However, task assignment only occurs when the agents are within the beacon's communication range. MAR-CPS allows visualization of this range, as well as the moment at which the communication link-up occurs (see Fig. 8b). Following link-up, the "follower" agent immediately begins its assigned task (e.g. movement to a target destination). In this scenario, MAR-CPS enables visualization of key mission features which would be otherwise invisible to spectators.

VI.   Conclusion

In this work, we presented an indoor environment for testing and debugging of autonomous vehicles, called Measurable Augmented Reality for Prototyping Cyber-Physical Systems (MAR-CPS). This work combines a motion capture system, ground projectors, autonomous vehicle platforms, and a communications network to allow researchers to gain a low-level understanding of the performance of perception, planning, and learning algorithms in real-time. The work extends previous capabilities of MIT's RAVEN testbed to allow display of latent information and uncertainty, allow perception of simulated environments, and serve as a teaching tool for spectators. Various experiments have been conducted using MAR-CPS, including forest fire management, planning for large-scale multi-agent systems, motion planning under uncertainty, and visualization of communication links between vehicles. Future work includes further investigation of applications in human-robot interactivity, as well as more complex applications in real-time perception and learning of the augmented reality environment.
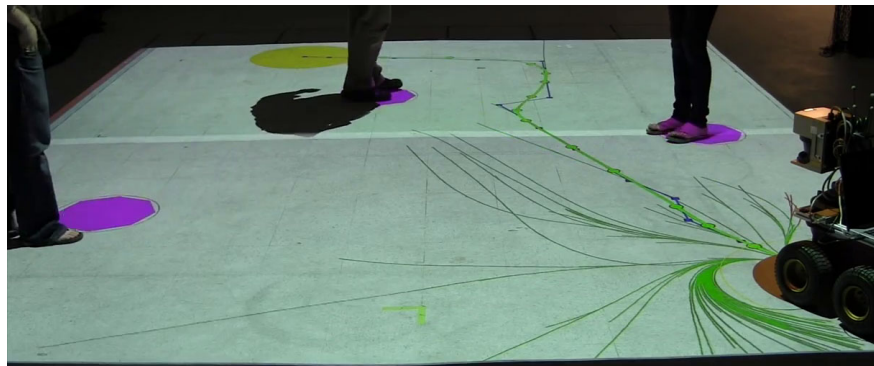
VII.   Acknowledgments
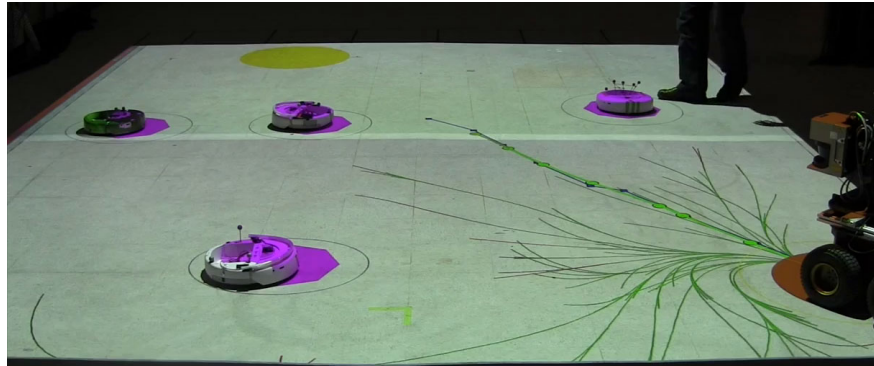
(a) A ground agent's planned trajectory based on perception of obstacles is projected and updated in real-time.
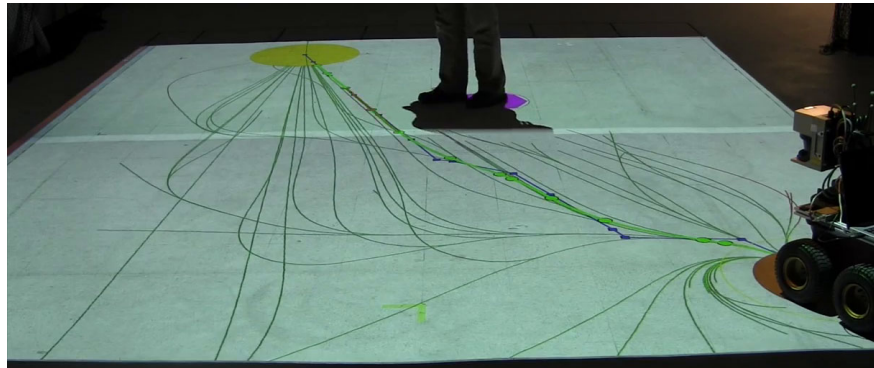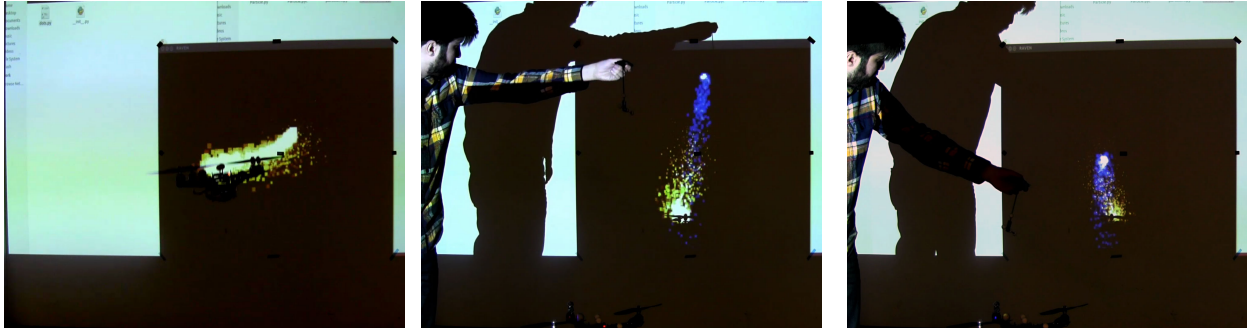

(b) Detection of human pedestrians for self-driving cars is visualizable in real-time using MAR-CPS.


(c) MAR-PCS enables visualization of complex scenarios such as path planning in multi-pedestrian environments.

Figure 6: Demonstration of motion planning under uncertainty in MAR-CPS.

(a) Visualization of quadcopter on fire using a particle simulator and projection system.

(b) Use of a water spout motion capture prop to quench fire is visualizable in MAR-CPS.

(c) MAR-CPS allows supports implementation of interesting human-robot interactivity demonstrations.

Figure 7: Human-robot interactivity using motion capture props in MAR-CPS.
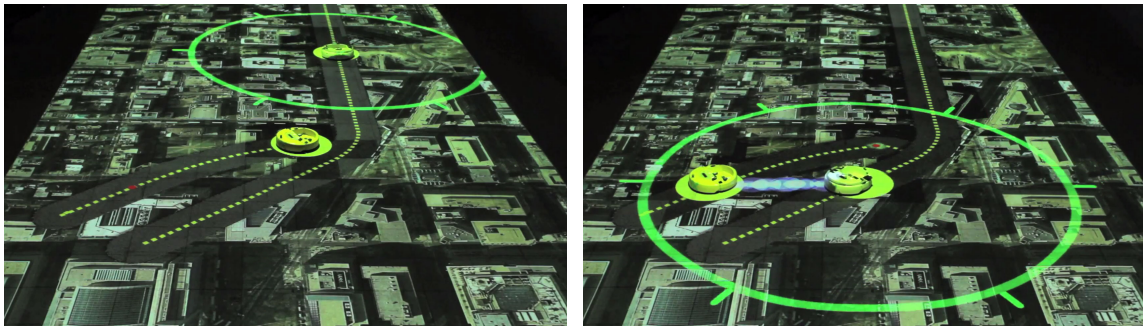
(a) A "leader" agent's radius of communication is indicated by a green circle surrounding it.

(b) When agents are within each other's communication radius, a link between them is established, and the transfer of information is visualized in MAR-CPS.

Figure 8: Visualization of communication networks in multi-agent systems.

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