8387-37 Autonomous Urban Reconnaissance Ingress System (AURIS™): Providing a tactically relevant, autonomous door-opening kit for unmanned ground vehicles

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ABSTRACT

The Autonomous Urban Reconnaissance Ingress System (AURIS™) addresses a significant limitation of current military and first responder robotics technology: the inability of reconnaissance robots to open doors. Leveraging user testing as a baseline, the program has derived specifications necessary for military personnel to open doors with fielded UGVs (Unmanned Ground Vehicles), and evaluates the technology's impact on operational mission areas: duration, timing, and user patience in developing a tactically relevant, safe, and effective system. Funding is provided through the US ARMY Tank Automotive Research, Development and Engineering Center (TARDEC) and the project represents a leap forward in perception, autonomy, robotic implements, and coordinated payload operation in UGVs. This paper describes high level details of specification generation, status of the last phase of development, an advanced view of the system autonomy capability, and a short look ahead towards the ongoing work on this compelling and important technology.

Keywords: Robotics, Autonomy, Unmanned Ground Vehicle, Urban, Reconnaissance, Gripper, Manipulation

1. THE CHALLENGE AND AURIS™ SYSTEM INTRODUCTION

The Autonomous Urban Reconnaissance Ingress System (AURIS™) addresses a significant limitation of current military and first responder robotics technology: the inability of reconnaissance robots to open doors, considered by humans to be a simple task. In terms of the development of robotic systems, there has been great progress in the use of robotic systems for things that robots are good at. Historically, robots have shown their value and even outperformed humans in specific areas where accuracy, repetition, or operation in dangerous areas is critical. Often left behind in this progression are complex human-operation-based robotic advancements. A classic example is driving; automotive engineers have been pursuing automated driving systems that can reliably track the flow of traffic around the vehicle, monitor the running condition of the vehicle, and then predict and avoid oncoming issues effectively [1,2]. Clearly, this is not a simple problem even in controlled environments and the current state of robotics does not lend itself directly to effectively handle similar issues in different applications.

AURIS™ is a product of the combined expertise of Boston Engineering Corporation's Advanced Systems Group (BEC ASG) and Autonomous Solutions Inc. (ASI). ASG technologies and projects include advancing Unmanned Vehicle technologies, developing biomimetic advanced AUVs (Autonomous Underwater Vehicles), creating advanced intelligent UGV payloads, non-conventional actuation technologies, integrated sensing solutions, and more. Autonomous Solutions is a leader in command and control software, vehicle and manipulator automation, multi-vehicle control, JAUS implementation, advanced sensing, 3D visualization, & controls. Under various programs, ASI has integrated resolved motion technology and reverse kinematic controls on vehicles ranging from the Packbot to commercial backhoes.

An inherently complex operation (though it may not seem that way to all) is that of opening doors. Aside from the vast variation of rotating mechanisms (knobs, handles, etc.), there is much variation in the location of the handle as well as the "response" (be it passive or active) of the door. The door opening action, simply put, is much more complex than humans might think. The process of door opening is ingrained in us through repetition but it is a fullbody action incorporating many different degrees of freedom. When attempting to isolate these motions into smaller, discrete components, the task for a robotic system is shown to be a much more complex undertaking.

Finer and seemingly more advanced subjects such as effectively opening a padlock with a key[3] and mimicking biped motion[4] are both good examples of tasks that roboticists are currently interested in developing solutions for, so why would a seemingly benign task of opening a door be a valuable military robotics project? Given the dynamics of MOUT (Military Operations on Urban Terrain) operations that rely heavily on robotic assistance UGVs, holes in the concept of operations emerge. One of these capability gaps for UGVs has been door breaching[5]. The brute force method of remote door ingress often necessarily involves explosives. There are however, significant opportunities where this is not a desired or reasonable course of action but this tactic is still used as there simply are no other time-effective methods while maintaining a safe standoff distance.

AURIS™ is responsive to these needs of the current military and homeland security forces. Manned missions to counter terrorists or insurgents are among the most dangerous. Good intelligence and situational awareness are key when planning a tactical strike or operation. As MOUT situations become more and more prevalent (it is estimated that 75% of the world's population live in cities as of 2010 [6]), the ability to attain rapid, robust and reliable ingress into buildings is a critical need. Previously concerned with primarily EOD and out-of-doors operations, UGVs are now being called upon to perform interior surveillance and manipulation in MOUT environments. With the rise of insurgency following the occupation of Iraq, for example, a unique threat has presented itself – an operative does not know what is behind doors. In a hostile situation, this lack of knowledge could prove deadly. Previous robotic solutions to this problem include the ThrowBot by iRobot and the Recon Scout from Recon Robotics[7] These robots allow for reconnaissance of a target area by tossing a robot through an open door or window. Unfortunately, target locations will not usually have an open door or window, which in turn, denies an operative quiet "entry" into the building using an unmanned platform. Current methods for an operative to enter a building or room through an enclosed passageway include; pneumatic door rams, robot-emplaced explosive charges, operative-emplaced explosive charges[8], the M-1030 door breaching round and mechanical spreaders [9]. All of these techniques are destructive and loud, eliminating much of any element of surprise. An unmanned system that is able to quickly, quietly and reliably open these passageways to scout the interior of a target hostile building or room is needed.

2. HIGH LEVEL REQUIREMENTS

The requirements set forth for AURIS™ from TARDEC speak directly to the advanced capability of the system as a whole. Unlike alternate door opening systems (other robot teams are working on door opening[10,11]), AURIS™ can provide advanced sensory knowledge in support of autonomy development including indications whether the door is spring loaded, locked at the knob/handle, or locked via a deadbolt.

To ensure the system is sufficiently robust for real-world implementation, it must include some inherent flexibility in terms of its initial conditions. When visualizing a realistic concept of operations, the process of door opening is a small component of the overall mission and therefore should only require a similar amount of available robot capability and resources. It is very likely that the user is not within line-of-sight of the vehicle and is thus forced into tele-operating via a small (and often low resolution) video feed. Using this video makes it unrealistic and unfit within the tempo of warfare for high precision placement and use of end effectors and other payloads. One of the differentiators of AURIS™ is that it allows a user to simply approach the door with the vehicle, activate the AURIS™ vision system, allow for the new onboard autonomy (in the form of an easily-attached kit) to ingress through the door, and then revert to operator control while inside. The initial conditions for detecting the door and knob are a critical component in the process, as it is paramount to ensure ease of use and reduced burden for the operator. Given this requirement, the vision and door recognition part of the AURIS system is being developed to function at many different initial offset angles and offset distances (between UGV and knob-axis) from the door.

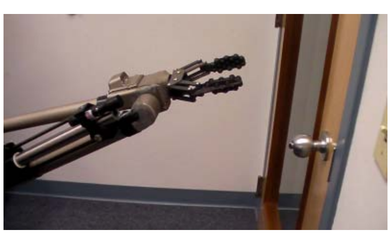
To the point of maintaining the speed and tempo of warfare; AURIS™ is being designed with challenging and specific time bogeys specified for ingress given different operational scenarios. Examples of the time limits required during testing are shown below.

Handle Type	Swing Direction	5kg Self Closing Force	Time Limit
Round Knob	Outward	No	30s
Round Knob	Inward	No	60s
Lever	Outward	Yes	60s
Lever	Inward	Yes	120s

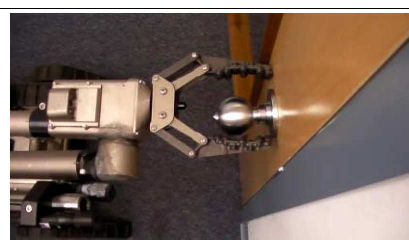
Figure 1: Time Constraints during AURIS™ Phase II Testing

3. DEVELOPING A SPEC: USER TESTING WITH CURRENT ROBOTIC SYSTEMS

Prior to system engineering efforts, the team performed robotic system evaluation in the current application of UGVs and door opening with a highly-trained operator from the Massachusetts State Police Bomb Squad. The Trooper spent significant time with Boston Engineering staff running through the common steps of door ingress with the State Police's iRobot PackBot. The Trooper was able to approach and align with the door, however had immediate trouble when attempting to grip around a spherical knob. Challenges to the gripping and opening included ability to accurately align the UGV with the axis of the knob, the physical interaction of the gripper with the smooth round knob, the lack of degrees of freedom in the gripping action, and the inability to see the knob sufficiently well and with the appropriate viewing angle to be able to manually place the gripper on the knob. This last point was critical for opening the door as the gripper demanded a level of exactness in the grasping to be able to hold the spherical knob sufficiently to turn it. The Trooper was able to open the door from start to finish in a total of approximately five minutes. The secure gripping and effective rotation along the knob's center axis took over four minutes (80%) of this time. This suggests that over the other 20% of the overall mission being other vehicle actions and motions does not represent the largest area for benefit in the maintaining of operational tempo of tactical missions. Timing is a very important issue for Bomb Squad and other operators for obvious reasons, as situations change very rapidly or demand rapid intervention. It should be noted that this five minute duration was with an expert user, on a standard office door, on a flat floor, and the operator could see the robot, the arm and the door. The Trooper reported to the team that other instances, one in a critical life-or-death situation have taken thirty to sixty minutes to open doors; depending on the door, location of jamb, and whether the UGV was on flat ground or not. The required upgrades to UGVs and grippers to perform this operation are clear: 1) a method for rapidly identifying the knob in space and determining its location, 2) including compliance in a manner that does not demand that vision, arm, and gripper accuracy be unreasonably high, 3) an effective method of maintaining rotation about the central axis of the knob, 4) applying the appropriate number of degrees of freedom to open the door without adding cognitive burden on the operator or causing the gripping implement to fall off the gripper. This latter point was a major component of the five minute door opening procedure.
A series of images from Massachusetts State Police Bomb Squad testing from Phase I are shown below. This is being used to guide the current development of the Phase II AURIS™ system.



1. Approaching the Knob



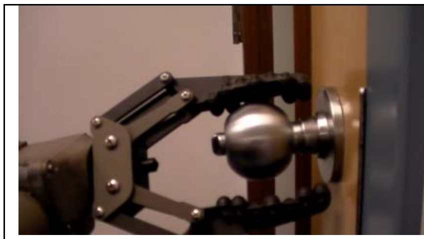
2. Driving Gripper into Door "Near Knob"

3. Misalignment Caused by Inferior Capability of Two-Fingered Gripper

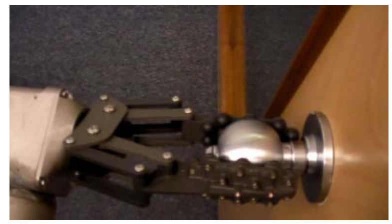

4. Turning the Gripper while Misaligned


5. Gripper Slips off; Lower Finger is Hitting Flange


6. Reopen Gripper and Try Again


7. It is easy to misalign off Axis while in Manual Mode


8. After 4+ minutes, Gripper was aligned onto Knob


9. Gripper Turns Knob; Starts to Lose Grip Due to Angle of Arm


10. Gripper Pulls Door Open by Backing Up Base


11. Gripper Continues Backwards as User Adjust Base


12. As knob angle increases, base adjustment necessary (no compliance at attachment to arm or at grips)


13. Robot continues to back up, User adjusts base slightly

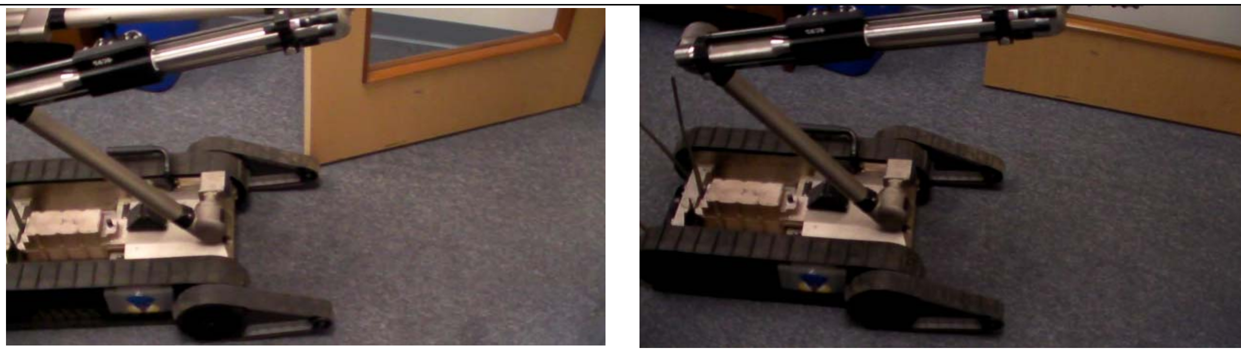

14. Gripper is at limit of grip; different conditions would have seen gripper release by now


15. Gripper opens and door (unsprung) left slightly ajar


16. Robot backs away from door


17. Base turns away from door (to its right as shown)


18. Robot driven up until “flipper” can move door aside



19. Robot Swings Door Open with “Flipper” 20. Door swung out of way, robot proceeds through

Figure 2: Images from Massachusetts State Police Vehicle Demo at Boston Engineering in Waltham Ma

Additional testing was conducted at Autonomous Solutions’ facility in Logan, Utah. An EOD Staff Sergeant and EOD Senior Airman were asked to demonstrate proficiency in manually opening common doors with a UGV system. Their approach was broken down into five separate segments which, when combined, provide the overall process of UGV ingress; positioning the vehicle base, positioning the vehicle arm, grasping and turning the knob/handle, pulling/pushing the door open, and traversing through the doorway. The figures below show both the quantity of missed attempts, mistakes and retries, and the average time of completion broken down into different segments in the door opening process.

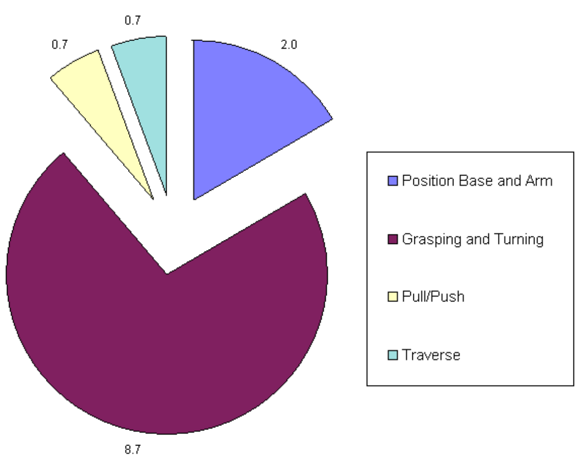


Figure 3: Average Missed Attempts, Mistakes or Retries

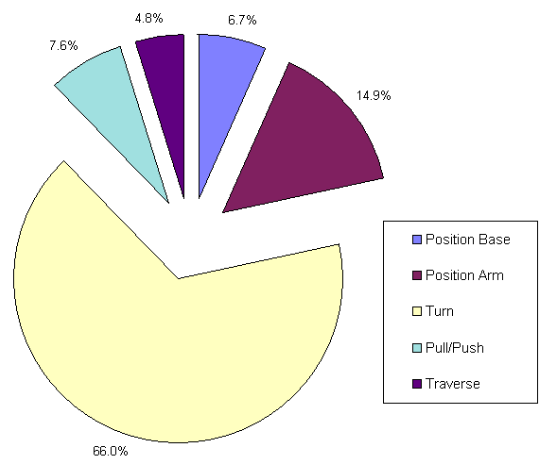


Figure 4: Duration of Each Subcomponent During User Testing

4. PHASE I SHORT REVIEW

AURIS™ enables advanced interior building reconnaissance with platform independence and removes the disadvantages of current operator-intensive systems based on operator manual control. It is based on an existing software and controls solution that has been implemented on both Talons and Packbots (among others) and has thusly provided a Phase I project that not only developed the system design and determined the required capabilities of the platform and manipulator arm, but demonstrated feasibility through the use of existing technology applied towards the challenge of door-opening and pass-through. The effort did not represent a new “university research program” but created a functional solution and performed feasibility tests in Phase I that proved the advantages of its approach backed up by initial feasibility experiments, design tradeoffs, and feasibility analysis. The team was able to show robotic door opening with semi-autonomous control in Phase I including the following:

- ❖ Autonomous 3D Scan of Doorway
- ❖ Autonomous Door Knob Segregation
- ❖ Manual Doorknob Selection
- ❖ Autonomous Arm Motion to Grasp Knob with Gripper
- ❖ AURIS™ Gripper Manually Commanded to Turn Knob
- ❖ Semi-Autonomous Vehicle Base Path Pulls Door Open
- ❖ Autonomous 3D re-scan of doorway
- ❖ Autonomous Indication of Open Path through Door
- ❖ Manual Placement of Way Points to Define UGV Path
- ❖ Autonomous Navigation of Way Point Path through Doorway

The team performed the UGV, arm and path control during the phase to the level where the AURIS concept was proven feasible and ready for follow-on efforts. These follow-on efforts (Phase II) are now underway. The following sections provide some detail in the status of a few key components of the autonomy portion of the AURIS™ system.

5. INTERFACE DEVELOPMENT and CURRENT STATUS

A key benefit to the AURIS™ door opening user interface is its ease of use for this normally complicated task (as shown by both Air Force EOD and State Police Bomb Squad Personnel). The user interface is coupled to perception and planning systems in such a way that the user is informed of what is detected and how the robot is going to proceed in terms of base and manipulator motions. At any point in the ingress task, the user can override a detected location or the planned path or simply take over command of the robot for tele-operation. Once the user has finished an override, the autonomy system can resume the next subtask. One example of this would be that the user wants to perform the knob grasping in a manual mode but then have the UGV open and drive through the doorway on its own.

In its simplest form, the user can select from the knobs that AURIS™ detects and then activate the sequence for full autonomous motion. The user interface contains controls for adjusted wall locations, door orientations, knob type, object positions, and vehicle path. Since the knob detection system may from time to time incorrectly determine door knob type at a distance, the user has the option to select a position in the video as the target knob instead. The AURIS™ team is also investigating more sophisticated semi autonomous methods of keeping the user in the control loop at a higher level than simply primitive base and arm motions. Several concepts are scheduled to be tested with end users to refine layout and available control options. The current user interface is shown in the following figure; note that it is rudimentary for development purposes at this time.

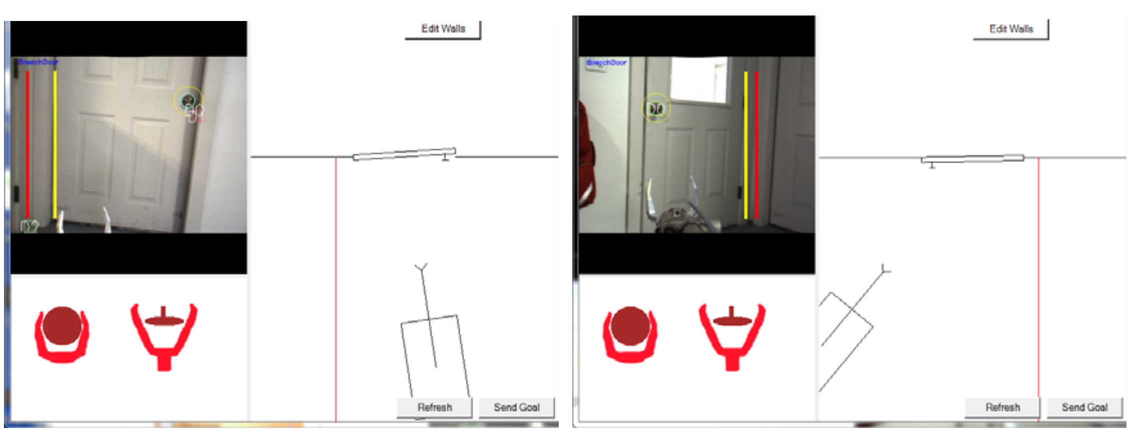


Figure 5: User Interface (Advanced User) Showing the Doorway Configuration and Detected Doorway Attributes (Knob and Hinge Axis of Rotation)

6. VISION AND AUTONOMY SOFTWARE CURRENT STATUS

The AURIS™ system uses machine vision techniques in combination with 3D sensing to aid in perception of the doorway environment. The perception system performs three main tasks; door recognition (knob position and door angle), door knob tracking, and obstacle detection. Door knobs are detected using segmented color regions along with 3D features based on object size, height, and offset from surrounding planes. Based on a small database of round and lever knob types, the system currently detects knobs approximately 90% of the time within a distance of 2.5 meters and within a 30 degree angle from the knob. The following figure shows the system detecting edges and knobs.

Figure 6: Top left image shows edge detection highlighting candidate wall corners and door edges. Top right and bottom show examples of correctly classified door knob regions

The door knob is also tracked and used for the door grasping procedure to account for errors accumulated from base motion odometry or from joint encoders. The tracking uses a combination of the features from the recognition system and 2D texture features to maintain accurate position (as shown in the following figure). These tracking techniques have been used to reliably position grippers to within five centimeters of the door knob center.

Figure 7: Door Tracking: Red circle indicates knob center, and white is target location to servo towards

Finally, obstacle detection is performed using a height grid while marking grid cells containing points above a manageable track height as obstacles. In the final stage of clearing the doorway, (has after the door has been opened), a drive-able path is planned through this grid that accounts for walls, the doorway, and any other obstructions.

7. A LOOK AHEAD

Tactical relevance and developing a system suitable for fielding and commercialization has been a focus of the AURIS™ program to date. The team is working to ensure that commercialization is possible and that the product can be fielded. To this end, the team has been developing the system to be modular and versatile to enable several versions, each with a unique individual target market.

TARDEC's mission (fully autonomous and fully capable AURIS™) requires all the major components of the system: autonomy, 3D vision, novel gripper, UGV interface, sensing system, base and arm coordination, and door opening-specific feedback loops. There is clearly a use for this system in many military operations. It is however likely that the largest user group for a door-opening UGV technology is the first responder community including police, HAZMAT, SWAT, Bomb Squad, and TSA, and more. These teams traditionally have significantly lower available budgets for unmanned systems purchases than their military counterparts. Additionally, cost-point goals for a targeted technology should probably be based on the available budgets at Captain and lower levels (discretionary funds) to make the system more likely to be adopted.

For Phase II, the team intends to perform a series of development, testing, and then internal milestones / demonstrations to show that the technology performs as desired. This ongoing Phase II work includes the development of a pre-production prototype system for door opening with versatility for other missions. During Phase II the team is coordinating efforts with platform manufacturers and with appropriate points of contact in future UGV programs (for example: AEODRS) such that the system (particularly its interface to the UGV) is designed appropriately and optimally for transitioning.

Since Boston Engineering's Advanced Systems Group provided novel prototype hardware and sensor testing and Autonomous Solutions provided prototype software in Phase I, AURIS™ has many advantages in terms of development, integration and testing. The work in Phase I to create these prototypes to prove feasibility was based on existing technology or technology already in development where possible. This directly enabled an advanced assessment of the specifications for the field-deployable system that is currently in development in Phase II.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

[1] Satterfield, B., Choxi, H., Salamon, A. and Drewes, P. “Advancing Robotics: The Urban Challenge Effect.” Journal of Aerospace Computing, Information, and Communication, Vol. 5. Dec 2008

[2] Jamson, H., Merat, N., Carsten, O., and Lai, F. “Fully-Automated Driving: The Road to Future Vehicles”, Proceedings of the Sixth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design (2011)

[3] DARPA-BAA-10-29: “Autonomous Robotic Manipulation Hardware Track (ARM-H),” 02 Feb 2010

[4] Tomizuka, M., Abu-Akeel, H., Atkenson, C., Et-al. “Soldier Protective Clothing and Equipment: Feasibility of Chemical Testing Using a Fully Articulated Robotic Mannequin.” National Academies Press, 2008

[5] “Unmanned Ground Systems Roadmap,” Robotic Systems Joint Project Office, July 2011

[6] http://www.globalsecurity.org/military/ops/mout.htm

[7] Barnes, Mitch, H. R. Everett, and Pavlo Rudakevych. ThrowBot: Design Considerations for a Man-Portable Throwable Robot. No. 2371. SPAWAR, Joint Robotics Program. San Diego, CA, 2005. 1-10.

[8] Geibel, Adam. "The Shotgun Approach." Special Operations Technology 25 May 2004

[9] Ewing, Lee. "Law Enforcement Seeks Robots to Counter Vehicle Bombs, Aid SWAT Teams." Unmanned Systems Aug. 2008: 16-19

[10] Gray, J., Campagna, F. “Human-Like Characteristics for High Degree of Freedom Robotic Door-Opening End-Effector,” Proceedings of SPIE Vol. 8045 (2011)

[11] Craft, J., Wison, J., Huang, W., Claffee, M., Phillips, E. “Aladdin: a semi-autonomous door opening systm for EOD-class robots,” Proceedings of SPIE Vol. 8045 (2011)