ROS-DOE: Leveraging Open-Source Robotics Software for the DOE-EM Mission – 17181

Paul Hvass*, Morgan Quigley**, Mitch Pryor***, Paul Wood*
* Southwest Research Institute, paul.hvass@swri.org, paul.wood@swri.org
** Open Source Robotics Foundation, morgan@osrfoundation.org
*** UT Austin Nuclear and Applied Robotics Group, mpryor@utexas.edu

ABSTRACT

In order to establish a common software framework for its robotic systems, the United States Department of Energy – Environmental Management (DOE-EM) is considering the possibility of extending the Robot Operating System (ROS) open source robotics software to address the varied, complex challenges facing DOE-EM. The effort, preliminarily called ROS-DOE, would enhance the reliability, robustness, security, and user friendliness of ROS to meet the requirements of the nuclear waste remediation mission, and those of DOE as a whole. As envisioned, the ROS-DOE program would also support rapid progress to mature cross-cutting capabilities including supervised autonomy, interoperability with off-the-shelf industrial equipment, and physics-based robot simulation (i.e., Gazebo).

This paper provides background context about the current state of ROS software and its supporting community, surveys DOE-EM needs and requirements for robotic solutions, and analyzes the gaps between the current state of ROS and those needed for DOE-EM robotics. It then identifies new capabilities that are recommended for ROS-DOE and outlines software development practices that could be leveraged to blend the best of the open-source world with high-reliability software development practices.

INTRODUCTION

In the 1990s, under the Robotics Technology Development Program within the Crosscutting Programs initiative and other robotics projects, DOE-EM invested substantial funds in advanced robotics software R&D for nuclear waste cleanup and processing. The technological achievements of this program were groundbreaking and included demonstrations of what is still considered advanced robotics: high degree-of-freedom (DOF) kinematic motion planning, fault-tolerant and modular robotics, intuitive 3D graphical user controls/interfaces, and process intelligence.[1] Yet today, we see only a few instances of these groundbreaking technologies deployed within DOE-EM. In many cases technology was lost as personnel changed or as new generations of computers, languages, and sensors made these historic software advancements incompatible or obsolete.

Without a community of continuous users for the technology to transfer to, progress was lost. Equipment was disassembled and stored and sometimes cannibalized for other experiments. Incredible state-of-the-art software is archived and/or inaccessible to the greater research community. This situation in which robotics research is trapped or lost as a result of project and personnel turnover is not unique to DOE. The same thing was happening for decades within academic robotics R&D, as PhD students graduated and funding varied with each new political administration. That is until the Robot Operating System (ROS) was launched in 2007.[2] ROS is an open-source software framework for advanced robotics R&D. With an estimated 113,000 ROS users worldwide, ROS has radically increased the efficiency and pace of progress in robotics software development and it has led to a new generation of robotics startups and products (Fig. 1).

Fig. 1. ROS is the framework of choice for these widely varied applications.

ROS includes many of the capabilities required by DOE-EM robotics use cases including 3D perception, navigation in unstructured environments, dexterous manipulation, and supervised autonomy. But while these efforts are comprehensive and widely accessible, there is not a comprehensive methodology to assure that developed software meets any industrial or other standard for quality or safe use. Given the potential of ROS to accelerate and support the use of robotics to reduce the costs related to DOE-EM's mission, the authors suggest that DOE undertake the development of ROS-DOE to build on the capabilities of ROS and upgrade its core to provide a secure, robust, and reliable software framework so that it can serve the unique challenges faced by the DOE-EM robotics development community, deployed across the spectrum of air, ground, and submersible robots, for emergent and routine purposes.

The health, safety, and economic benefits of robots are well understood by DOE-EM; its 1990s investment in robotics is evidence of this. However, to build robots that thrive under the extreme/unknown environments faced by DOE-EM, the new capabilities of ROS software are needed in a robust and reliable form that can be quickly assimilated by any DOE-EM robotics practitioner (Fig. 2).

Fig. 2. The community of contributors and beneficiaries to ROS-DOE is potentially vast.

Fig. 3. (Left and Center) Drum explosion accident at WIPP. Robots were needed to assess damage, determine root cause, and act to contain any further spread. (Right) Hot cell master/slave manipulators for routine radioactive material handling [3] could be replaced by off-the-shelf industrial robots enabled by 3D sensing and smart software. Source: DOE-EM Presentation to UT Austin Nuclear and Applied Robotics Group (NRG).

DESCRIPTION

Similar in many ways to the robots that ROS has enabled, the mission for DOE-EM robots includes a wide variety of tasks, all aiming to keep humans safe while improving the efficiency of emergency response, site security, nondestructive inspection, and routine waste remediation tasks (Fig. 3). The diversity of tasks calls for robots that fly, roll, walk, and swim. Any of these robotic forms may have sensors to perceive and/or manipulators to interact with the world. ROS can provide a powerful modular software framework for all of these tasks, but because ROS arose from research and service robotics, some additional development is needed to repurpose it for DOE-EM tasks. What was needed was a gap analysis to determine which capabilities are already adequately supported by ROS. The analysis has identified specific new or underserved capabilities that are needed for a DOE-EM robot software framework.

DISCUSSION

The gap analysis began with a survey of five diverse near-term specific DOE mission examples. Additional future mission examples were also considered at a high level.

DOE-EM Mission Examples

This section briefly documents a few illustrative DOE-EM missions where the inclusion of ROS-DOE would prove beneficial:

- Inventory Surveillance and Security (SNM) [4]
- H-Canyon Inspection (SRS) [5][6][7]
- Nondestructive Testing (NDT) Inspection (LANL, SRS and elsewhere) [8]
- Safe Use of Industrial Manipulators in Confined Spaces [9]
- Tank inspection (AY-102 at Hanford) [10]

These five examples provide a reasonably diverse overview motivating the development of mobile manipulators, radiation-tolerant systems, glovebox manipulation, and customized robotics. Most DOE-EM missions will see their requirements in some combination of these missions and ROS-DOE will develop core capabilities to serve this broad range of DOE-EM missions.

Inventory Surveillance and Security. A common but mundane task across the DOE complex (and the nuclear industry in general) involves taking inventory and inspecting long-term storage facilities for waste, archival, or temporarily stored SNM for radiation contamination (Fig. 4). Operators completing these tasks are often exposed to higher than normal background radiation which is ideally avoided or minimized. It is also desirable to complete these tasks more comprehensively and with higher frequency than is possible using human operators due to radiation limits, cost, and the impact of drudgery. To address these and other issues, UT Austin and LANL have developed the ability to complete these tests using a fully autonomous mobile manipulator. Full autonomy allows for the system to operate in secure environments without the need for wireless or other forms of electronic communication, which is a strict security requirement. If contamination is found, operation ceases and a Radiation Contamination Technician (RCT) is audibly summoned. With no time constraint, the platform is able to perform a more frequent and comprehensive inspection which includes label verification, object recognition, pose estimation (has a container been moved), radiation emission detection, and alpha contamination.

Fig. 4. (Left) Inspection of low-level waste at WIPP storage facility.[3] (Right) A mobile robot platform developed at UT Austin and LANL to perform inventory, radiation survey, and detection of alpha contamination in storage facilities for SNM. Source: UT Austin NRG.

H-Canyon Inspection (SRS). H-Canyon is the only hardened nuclear chemical separations plant still in operation in the United States. In 2014, the Inspection Crawler (IC) was deployed (Fig. 5) to inspect the H-Canyon Air Exhaust Tunnel (CAEX) which connects the canyon to the sand filters. The tunnel must be inspected regularly to ensure its structural integrity which is complicated by the debris, water, low-level radiation, and other hazards. The 2014 deployed IC tipped over in the tunnel and was later put back on its wheels by the Recovery Crawler (RC) in June 2015. It was determined that the IC would be unable to adequately perform its inspection function and inspection continued with the RC, which was able to traverse most of the canyon and record video for evaluating the shaft's structural integrity. This was considered a success, as the RC was not designed with detailed inspection as its primary purpose. Ideally, future platforms will be able to:

- Provide complete, high-quality videos of all the walls and ceilings, including those difficult-to-reach sections behind the obstacles or covered by debris.
- Traverse debris and water in the tunnel.
- Provide autonomous redundant safety capabilities to assure the system cannot be tipped or damaged by operator-commanded moves in uncertain environments.

- Provide additional and more frequent inspections including nondestructive testing (such as neutron radiography) and contact sensing.

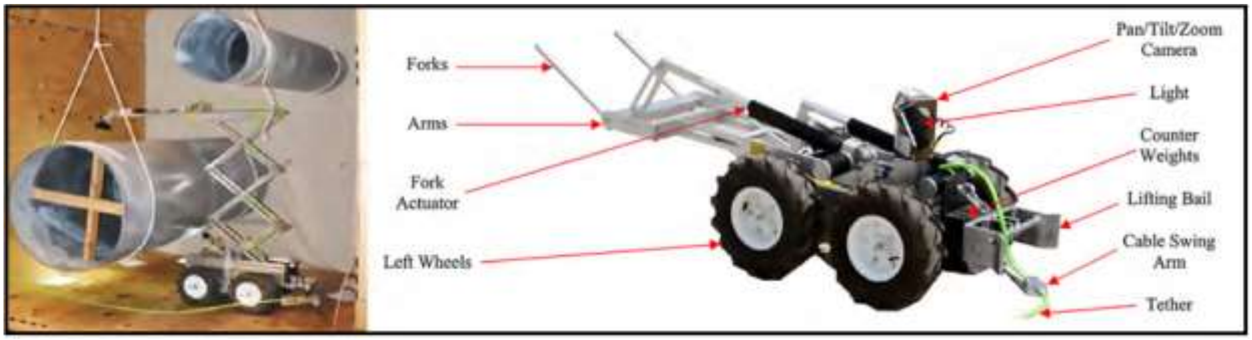

Fig. 5. (Left) The 2014 Inspection Crawler (IC). (Right) The 2015 Recovery Crawler (RC). Source: SRS Report.[6]

Nondestructive Testing (NDT) Capability for Inspection. NDT capabilities would also be relevant to other DOE-EM applications (Figs. 6 and 7). Penetrating radiation has been used for imaging purposes since 1895 when Roentgen discovered X-rays. Emerging applications such as inspecting cargo containers, characterizing improvised explosive devices, inspecting waste storage containers, and evaluating the structural integrity of aging structures have all reinvigorated efforts using tomography and compact radiography.

Fig. 6. Recovery Crawler in H-Canyon Air Exhaust Tunnel (CAEX) which connects the canyon to the sand filters. The RC approaches a puddle (left) and highlights the corrosion on the walls, then (right) traverses the 13-inch-deep puddle.[5]

Additionally, unusual environmental threats, like those from underwater oil spills and nuclear power plant accidents, have caused renewed interest in fielding radiography in severe operating conditions. Today any particle type can be sensed with an increasingly wide range of digital detectors to image almost any conceivable object in extreme environments. These severe operating conditions pave the way for sortable and remote handling systems, such as robots. While much nondestructive testing is conducted manually, there has recently been a growing interest in the development of robotic systems for NDT which ROS-DOE would enable for a broad range of NDT applications.

Fig. 7. (Left and Center) Inspection and inventory of surplus SNM at multiple DOE sites in response to contamination alarms or unplanned events at long-term storage facilities such as WIPP. (Right) characterization of poorly documented storage facilities such as the PUREX tunnels at Hanford.[3]

Safe Use of Industrial Manipulators in Confined Spaces (Fig. 8). Robotic technologies for factory automation have improved dramatically in terms of cost and reliability over the past two decades. The 1990s saw a price-performance improvement of 12 times and wide adoption by the automotive and other manufacturing industries. Today's systems are capable of 24/7 operation with life spans exceeding 80,000 hours. What has generally not improved on the factory floor is the autonomy of these systems and their ability to react to uncertainty or unscheduled events. The modus operandi is still to stop all activity and notify the line manager of a problem with a flashing light. For glovebox manufacturing tasks, it is not possible to leverage any given task uncertainty and the relatively low-volume activity. To illustrate this, consider the glovebox application MOX fuel processing, which has the potential to extract value from the nuclear waste stream. MOX fuels are created from unseparated spent nuclear fuel rods (or decommissioned weapon components) containing long-life fission products such as americium-241, of which there is no current domestic supply. Production of these products can:

- reduce hazardous waste (both quantity and nuclide half-life),
- create non-proliferation reactor fuels material, and
- extract valuables including americium (smoke detectors, energy exploration) and medical isotopes.

Fig. 8. (Left) Radiograph of non-3013-packaged solids with a container breach. (Center) Industrial manipulator used to produce neutron radiography images in both a reactor beam port and using a portable neutron source. (Right) Image of spent nuclear fuel rod with robotic system with gadolinium and tungsten inclusions.[8]

Although some MOX fuel fabrication processes are well understood and feasible for high-volume manufacturing, many of the fuel sources are finite and there is a desire to test new fuel mixtures in controlled environments. Thus there is a need for a small-batch, flexible manufacturing capability that protects operators from high levels of radiation (Fig. 9).

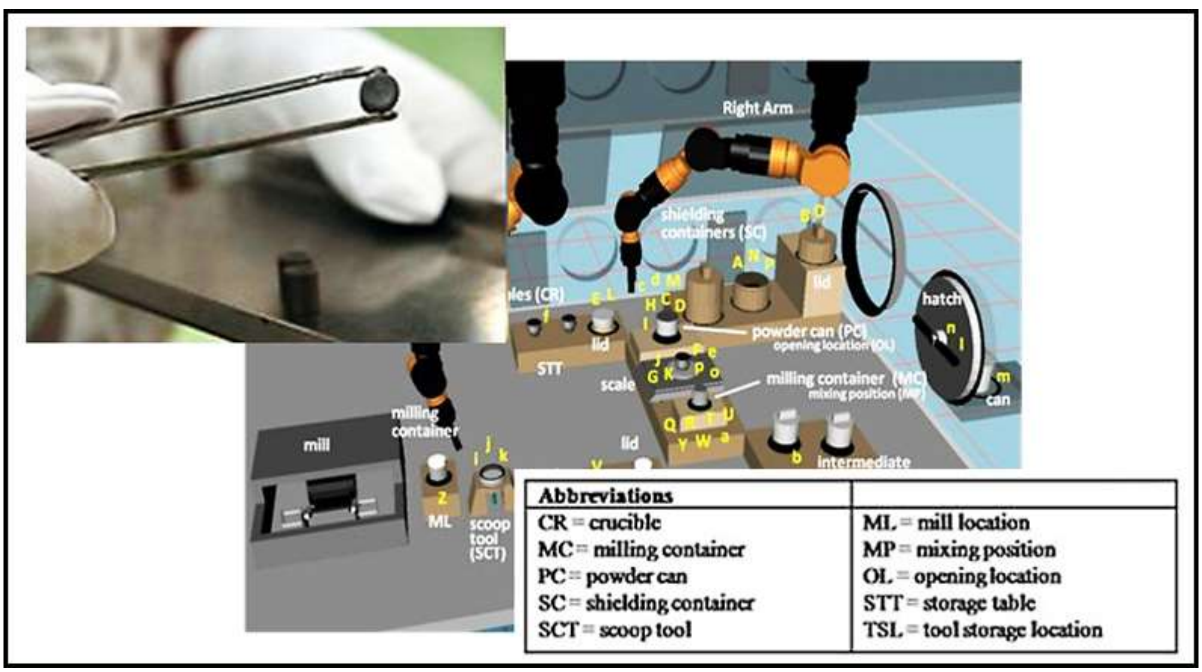

Fig. 9. A MOX fuel pellet and proposed glovebox radiochemistry and manufacturing cell for americium-241 extraction.[9] Source: *UT Austin NRG.*

Tank Inspection and Clean-out. Recently, traces of waste were found in the annulus of the AY-102 double-shell tank storing radioactive waste at the Hanford site, prompting the need for developing inspection tools that can identify the cause and location of the leak. This particular application – more than many others – may require the development of novel hardware that can access the environment. Yet, even in this case, components of ROS-DOE would be critical including nodes supporting sensors and a physics-based development environment such as Gazebo. Fig. 10 shows three possible entry points for inspection in the AY-102 tank:

- refractory air slots through the annulus
- leak detection piping
- ventilation header piping

Other ROS-DOE Relevant Tasks

The missions outlined above span multiple robotic domains and are only partially representative of the broad range of missions facing DOE-EM. The capabilities of robots in each mission have been advanced by ROS and can be adopted to support ROS-DOE.

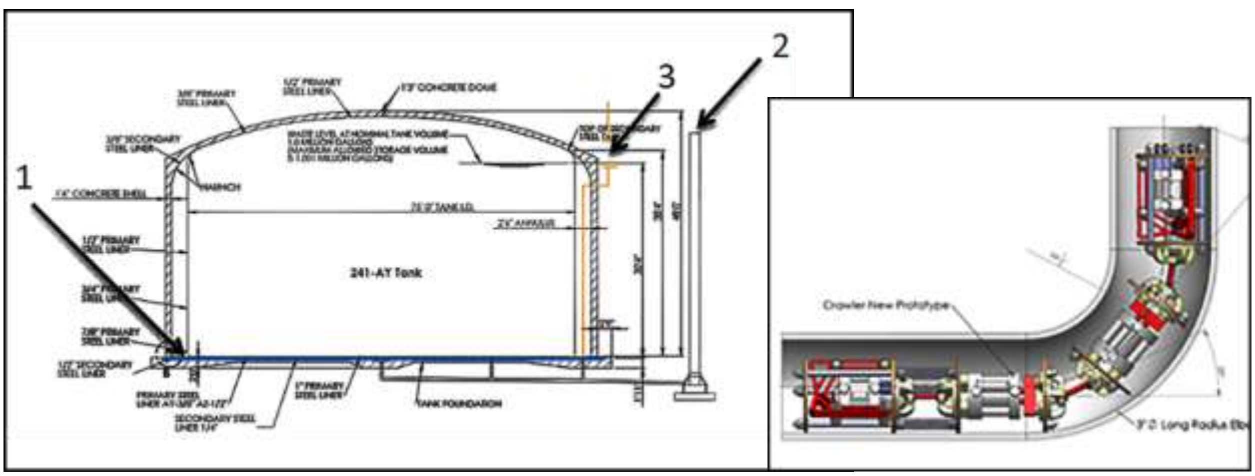

Fig. 10. Left: Inspection entry points at AY-102 double-shell tank.[10]

Remote Unmanned Aerial Vehicles (UAVs).
Tasks: Monitor and secure outdoor buildings, containment areas, perimeters, and warehouses; implement long-term monitoring of remote locations; rapid or routine nuclear forensic analysis; explore and inspect carefully selected indoor environments.
Challenges: Tele-operation is difficult in environments where crash landings and other errors cannot be tolerated. Also, motive methods for UAVs can spread contamination or disrupt sensors.
Additional DOE-EM Mission Examples:

- Drone photography/video of external concrete (containment and cooling tower) cracking (PNNL)

- Combined robotic unmanned air system capable of responding to off-normal events (LANL)
- Large-scale survey missions (INL)
- Ortho-rectified scaled geometrically corrected aerial photos (SRS)

Autonomous Ground Vehicles.
Tasks: Monitor and secure outdoor buildings, containment areas, perimeters, and warehouses; support air assets; provide data links and/or power for other systems; perform material transfer; provide emergency response; explore and inspect buildings, vaults, tunnels, and mines.
Challenges: Limited battery life, mobility in debris fields; communication; security issues; broad range of environments that require broad range of solutions to be examined in terms of size, payload, and mobility.
Additional DOE-EM Mission Examples:

- Infrared (IR) flash thermography for flaw detection of degradation on the primary double-shell tank (DST) inside diameter (ID) from annulus (PNNL)
- Sensor and mobile device integration for surveying and mapping using smartphone and tablet interfaces (SRS and elsewhere). Sensing includes thermal, rad, seismic, etc.
- Response to human contamination alarm events for additional scanning or retrieving contaminated clothes and delivering smocks (LANL and elsewhere)

Manipulation (confined space or integrated mobile manipulation)
Tasks: Radioactive material handling, inspection and packing to reduce waste volume; mobile manipulation; anthropomorphic tasks for response in emergency situations.
Challenges: Human-robot interactions; redundant safety protocols, off-line planning; trajectory planning in confined spaces, autonomous grasping; maintenance; radiation hardening.
Additional DOE-EM Mission Examples:

- Material reduction for storage or re-use of SNM (LANL, Y-12, SRS)
- Inspection of transfer canisters (LANL, SRS, WIPP, etc.)
- Portable radiochemistry lab or emergency response

Remote Operated Vehicles (ROVs)
Tasks: Monitor and inspect flooded structures, spent fuel storage pools, and pipes; clean cooling systems for increased efficiency, activity in media other than water.
Challenges: Battery life and/or tethering; communication; fix and forget location; fragmented commercial base; miniaturization.
Additional DOE-EM Mission Examples:

- Drone photography /video of external concrete (containment and cooling tower) cracking (PNNL)
- Combined robotic unmanned air system capable of responding to off-normal events (LANL)

- Large-scale survey missions (INL)
- Ortho-rectified scaled, geometrically corrected aerial photos (SRS)

Non-traditional or Bio-Inspired Robotic Systems
Tasks: Exploring extremely small or hard-to-reach areas; hand-heavy or extremely high-dose material; long-term survey; short-duration missions (still camera or explosive deployment); intelligence gathering.
Challenges: Robust and validated designs; typically limited mission scope for long development times; battery life; physics-based simulation; large and diverse area of research.
Additional DOE-EM Mission Examples:

- Assess tank bottom integrity (PNNL, SRS)
- Traverse debris field for signs of survivors after Fukushima-like event
- Gecko-inspired mobility for wall and ceiling inspection (LANL)
- Autonomous gantry systems for swing-free fuel rod dry cask transfers to reduce exposure times
- Distributable communication nodes for increasing the range of mobile robotic systems

The use of ROS and ROS-I at UT Austin, LANL, Argonne, and elsewhere demonstrates its value for implementing robotics to meet the missions outlined above. Robotic systems using ROS are in various developmental phases from feasibility demonstration in an academic setting to system readiness testing in cold labs within the DOE complex. As with any robotic system, developers must fill any gaps in the capabilities of the operational software to ensure the system is robust and capable of completing its mission. ROS has drastically reduced or eliminated many of the daunting gaps for robotic systems found in DOE-EM environments, and UT Austin and LANL have collaborated to remove many more. This effort has helped the authors to better identify and focus their recommended efforts on the remaining capabilities necessary for ROS-DOE to be successfully deployed, which are summarized in Table 1.

Besides identifying how technical requirements for ROS-DOE might drive the expansion of ROS2 capabilities via the gap analysis, the authors also considered how ROS-DOE could be developed to remain compatible with ROS2 and benefit the open-source community. The authors recommend the following practices to unite the best of the open-source world with high-reliability software practices (Fig. 11):

- **Golden ROS-DOE Releases:** Changes originating from the ROS 2.0 community will be vetted by a software change control board before incorporation in ROS-DOE. Reviewed "golden" releases of the ROS-DOE core will be available as binary files to prevent accidental changes that might invalidate independent verification and validation (IV&V).
- **Run-Time High-Reliability Monitoring Utilities:** A fundamental approach to dealing with the open-source nature of ROS will be the establishment of

run-time monitoring utilities that check the control outputs from ROS against simple, easily checked criteria. For example, verification that the robot tool center point is within a bounding box could provide a significant degree of safety using an easily computable check. To provide isolation, use of a partitioned operating system such as VxWorks-653 could be used.

- **Core is Public, Applications are Government-Only:** The ROS-DOE core, which will be maintained by Open Source Robotics Foundation (OSRF), will stay open to the worldwide public and be known as ROS 2.0, sharing its innovations. Specific DOE-EM applications, which will be held on government servers, will be accessible to the government and authorized government contractors only.
- **Federated Repositories:** While the core and golden releases will be maintained at OSRF, the federated model of development will continue. New capabilities will migrate to the core once they are reviewed.
- **Designated Administrators:** Between golden releases, the ROS-DOE core software will be open to pull requests from anyone, but only the designated OSRF maintainers who are familiar with the ROS-DOE development practices will have administrator privileges to accept these changes.
- **Software Development Practices:** The core ROS team at OSRF already uses software development practices that have enabled unmanned demonstration vehicles to reliably drive on roads and in unstructured environments. Southwest Research Institute’s High Reliability Software Group will independently audit OSRF’s procedures to validate that a robust process is in place.

TABLE I. Gap Analysis of ROS Capabilities (Left Column) for DOE-EM Tasks

Notes: All components need to be ported to ROS 2.0 and reviewed; these activities are not included in the table.

1. Highly customized systems designed to enter tanks may require new navigation software given the probability of new navigation and motive modalities.
2. Likely to be supported by open-source community.
3. GUI tools needed – perhaps build on EU project ReApp.
4. Customize and upgrade existing training for DOE applications.

Color Key	Not Applicable	Create New	Exists (needs some upgrading)	Exists

	Inventory Surveillance and Security	H-Canyon Inspection	Automated NDT	Manufacturing in Confined Spaces	Tank	Gap
2D Perception						
3D Perception						
Build Systems						
Calibration						
Closed Loop Control					Note 1	
Communication Infrastructure						
Continuous Integration						
Cross-Platform (Linux, OS X, Windows)						
Data Security						
Diagnostics						
Documentation						
Drivers & Interfaces					Note 1	
Grasp Planning						Note 2
Localization					Note 1	
Logging						
Mapping						
Navigation					Note 1	
Pose Estimation						
Motion Planning					Note 1	
Real Time — Messaging						
Real Time — Monitoring						
Robot Geometry Library						
Developer Tools						
3D Setup Tool						
Command Line						
Integrated Dev. Environment						Note 3
Runtime User Interface						
Standard Robot Messages						
Software Verification & Validation						
Supervised Autonomy						
Training Curriculum						Note 4

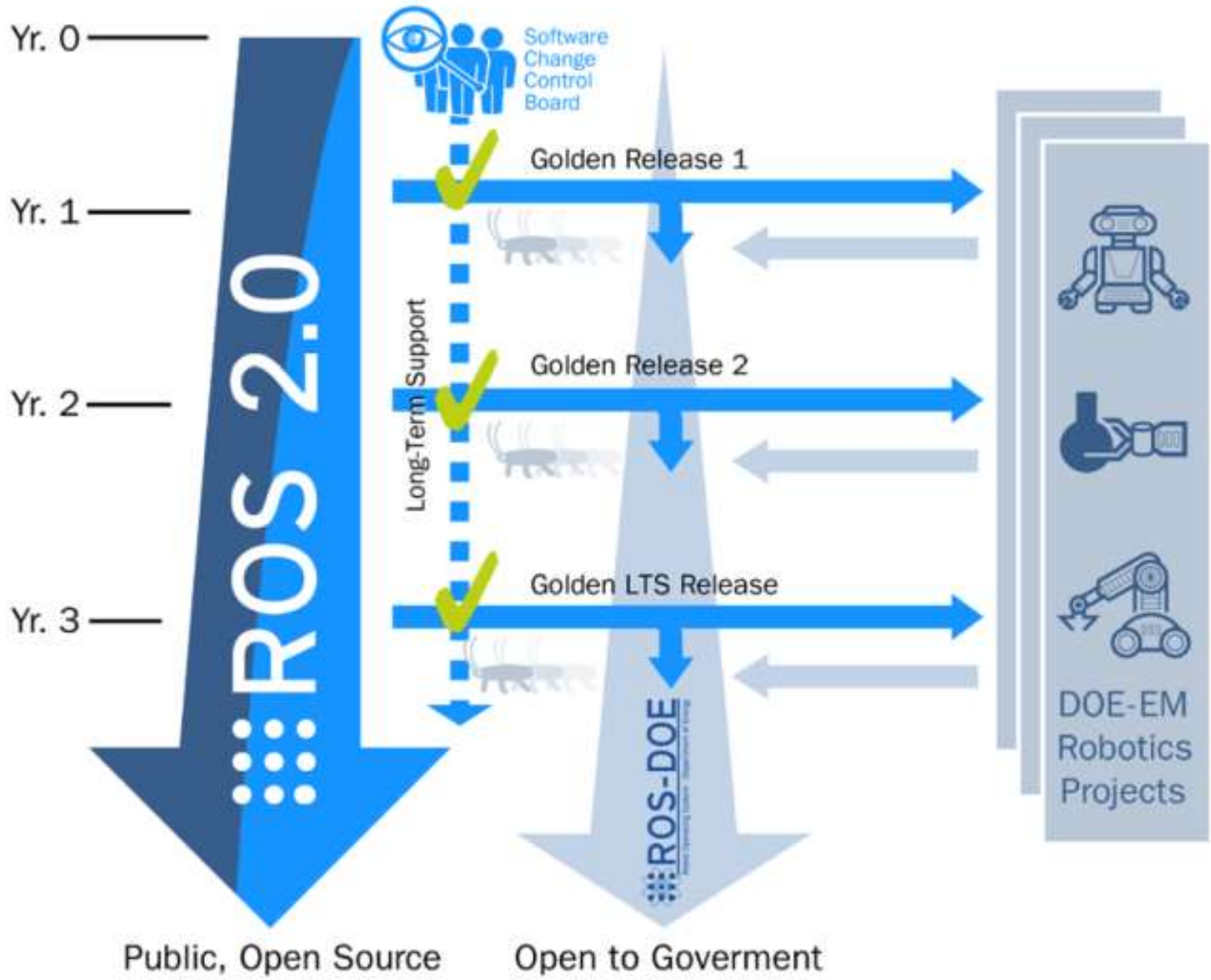

Fig. 11. Suggested ROS-DOE software development plan. As reliability and security are built in to ROS 2.0 packages, the proportion of code that constitutes ROS-DOE increases.

CONCLUSION

This paper has provided the background context for the current state of ROS software and its supporting community. It surveyed DOE-EM needs and requirements for robotic solutions, analyzed the gaps between the current state of ROS and those needed for DOE-EM robotics. It then identified new capabilities that are recommended for ROS-DOE and outlined software development practices that could be leveraged to blend the best of the open-source world with high-reliability software development practices.

REFERENCES

1. Noakes, M., Haley, D., and Vagnetti, R., "Deployment of remote systems in US Department of Energy Decontamination & Decommissioning Projects," *Conference on Decommissioning, Decontamination and Reutilization (DD&R)*, Idaho Falls, ID, USA, September, 2010.
2. Quigley, M., B. Gerkey, B., and Smart, W.D., Programming Robots with ROS: A Practical Introduction to the Robot Operating System. O'Reilly Media, 2015.
3. Rimando, R., "U.S. Manhattan project legacy: opportunities for advanced robotics in nuclear cleanup," 2nd Workshop on Robotics and Automation in Nuclear Facilities at the IEEE/RSJ International Conference on Intelligent Robots and Systems, Hamburg, Germany, September 2015.
4. Paffett, M., "Designing a container for safe, long term storage." *Actinide Research Quarterly* 2004: 132.
5. Tibrea, S., and Reid, L., "H-Canyon exhaust air tunnel inspections," IEEE/IROS 2nd Workshop on Rob and Auto in Nuclear Facilities, Hamburg, Germany, 2015.
6. Krikku, E.M., Hera, K.R., Marzolf, A.D., and Phillips, M.H., "H-Canyon recovery crawler," SRNL Pubic Report SRNL-STI-2015-00355, August 2015.
7. Pryor, M., and Landsberger, S., "Development of a graduate curriculum for automation in the nuclear domain," *Proceedings of the 2009 ASEE Annual Conference and Exposition,* Austin, TX, June 2009.
8. Hashem, J., and Pryor, M., "Performing neutron imaging of mock uranium fuel rods with a robotic manipulator," *Proceedings of the ANS Annual Meeting,* San Antonio, TX, June 2015.
9. Williams, J., Schulte, L., Pryor, M., and Landsberger, S., "A complete approach to reduce operator dosage in hazardous environments," *Proceedings of the ANS 3rd International Topical Meeting on Robotics and Remote Systems*, Knoxville, TN, August 2011.
10. Washenfelder, D., "Forensic investigation of Hanford double-shell tank AY-102 radioactive waste leak," *Proceedings of the 2014 Waste Management Symposia,* Phoenix, AZ, 2014.