Automation Toward Tetherless Robotic Operations in Nuclear Facilities – 17474

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ABSTRACT

Automation capabilities that enable communication-denied nuclear robotic operations have come of age. These layer over tethered operation or enable untethered systems for some operations. Teleoperated, tethered devices are traditionally preferred for nuclear remote systems. Tethers provide comm, power, and a means for mechanical extraction. They also restrict mobility and create additional failure points, and in some cases, circumstances preclude mechanical recovery by tether. Tethering has superb advantages where it is viable, but a subset of nuclear EM challenges compel mobile remote systems that forgo tethering. Tethering was essential at a time when autonomy or wireless comm could not accomplish viable operations, but now an emerging class of untethered exploration and service robots are compelling for situations where tethers compound waste and exposure, or are not viable. Technical advances in localization, modeling, planning, autonomy, integration and reliability have made it possible to augment tethered operations or operate altogether without tether in selective operations. Tether preclusion technologies include localization, perception, navigation, safeguarding and task prescription. These effectively accomplish tasks like waypoint following, wall-following, coverage patterning, navigate-to-goal, next-best view and many others. Although these are not yet general for the broad agenda of the nuclear complex, these are already useful for many operations. These provide a foundational base that can be built upon over time for more complex operations yet to come. As a context and analog study, the technologies are exhibited by robotically (without tether) modeling a coal mine with tracks and train cars. This is analogous to technology and operation that might apply for inspection of waste storage at WIPP or the PUREX tunnels. Autonomous exploration of this nature is within state-of-art and possible with or without tether.

INTRODUCTION

Teleoperated, tethered devices are traditionally preferred for nuclear remote systems, as they can provide comm, power, and a means for mechanical extraction. Tethers, however, are susceptible to failure and often restrict mobility. Also, some circumstances preclude recovery, negating the mechanical extraction advantage. Tethering has superb advantages where it is viable, but a subset of nuclear EM challenges compel mobile remote systems that forgo tethering.

Tethering was essential at a time when autonomy or wireless comm could not accomplish viable operations. The possibility now is a new class of untethered exploration and service robots that are compelling for situations where tethers compound waste and exposure, or are not viable.

Technical advances in modeling, planning, autonomy, integration, and reliability have made it possible to augment tethered operations or operate without tether in selective operations. Tether preclusion technologies include: a) multimodal sensing and semantic representation towards robust navigation, b) multimodal mapping and semantic classification in narrow, cluttered and dark environments, c) active perception combined with semantically-enhanced exploration, d) inspection to optimize the value of collected data, and e) optimized system design with enhanced payloads for radiographic and thermographic sensing. Planning for tetherless operation must prioritize safeguarding and egress above all else. Autonomy for specific applications exploits intrinsic structure, such as wall following through tunnels, and utilizes opportunistic comm where wireless connectivity is available. Tetherless systems, not component technologies, perform operations, so systemic integration matters above all else.

Fig. 1. Conceptual ground based and flying robots perform multimodal mapping.

Characterization and monitoring of vast facilities like tunnels and processing plants require persistent presence, substantial range of operation, and repeated sorties for sampling, data gathering, and trending over time (see Fig. 1). Additionally, there is cost of decontamination and operation for egress from a facility. There is need to acquire data over time. All these functions - persistence, data transfer, and preclusion of egress - were historically achieved by tethering to support long-term operations. Of course, these came with the attendant downsides of tether. These functions of energy recharge, data transfer, and preclusion of egress can now be achieved by docking stations to support protracted campaigns of tetherless operation.

Tethered and untethered systems are juxtaposed with consideration of lessons learned from past robotic deployments. Automation capabilities of localization, sensing (including radiation mapping), modeling, safeguarding and planning are profiled. A case study exhibits the technologies in action by exploring and modeling a mine tunnel as analogy to the PUREX 1 waste storage tunnel within the nuclear waste management complex.

NUCLEAR FACILITY INSPECTION

The majority of data gathering is currently conducted by human workers in protective clothing with consequences of cost, inefficiency, exposures and inability to even access many places that matter. Remote systems have emerged for important roles in dismantlement, tank cleanup, material handling and accident response. However, many essential operations are beyond the physical, technical or affordable reach of these conventional remote systems and human entries. Foremost among these is the need for robotically and autonomously acquiring, integrating and utilizing radiological, thermal, spatial and visual characterizations of inaccessible or highly radiated facilities (Fig. 2 shows a concept of multimodal mapping from robots in DOE facilities). An iconic example is the long, dark, sealed, humanly-inaccessible, PUREX tunnel containing a trainload of highly-contaminated equipment. The presented technologies are means to explore and rad-map such sites by deploying unprecedented sensing, modeling and planning on small flying and roving robots. Beyond invaluable characterizations, this capability is foundational to the autonomy that will preclude many future tethered entries, exposures and decontaminations for decades to come. Rad-mapping of facilities such as H-Canyon, WIPP and the PUREX tunnels can be performed by cognizant, sentient robotic technologies as described here. Moreover, this technology can revolutionize the perennial assessments, planning, prioritizations, safeguarding, accident responses and sustained facility monitoring. These are essential at nuclear facilities, long-term storage, and accident sites.

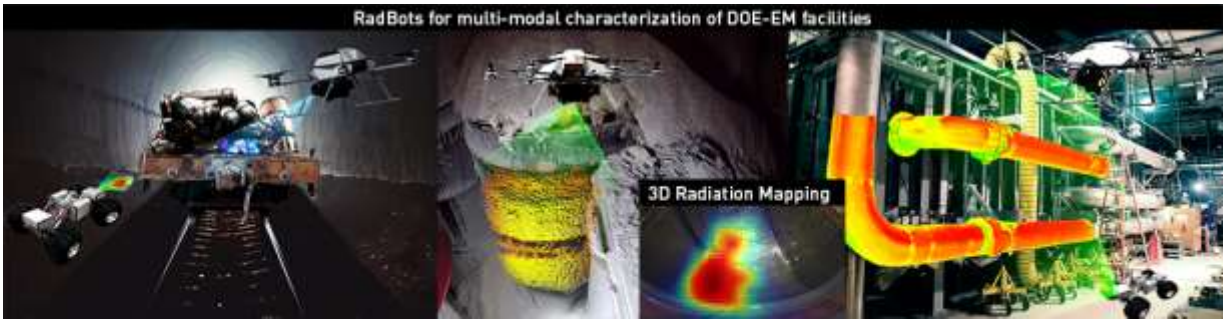

Fig. 2. Left image shows concept for exploration of a storage tunnel at PUREX by a ground robot and a drone. Center shows detail of 3D modeling and radiation mapping. Right image shows thermal mapping by upward view from a ground robot and down-looking from a drone.

Exploratory robotic mapping has evolved for non-nuclear purposes through decades of research and enterprise, so what is distinct for the unique challenges of nuclearized robotic mapping? Radiation imagers have slower frame rates than camera-and-scanner-only non-nuclear SLAM (Simultaneous Localization and Mapping). The best radiation imagers require stationary dwell time for each frame. Hence, the relevant imagers, not the fusion/planning, pace the autonomy and drive regions-of-interest and viewpoint planning in ways that visual-spatial sensing does not. Radiation and thermal imagers are also bulky and massive relative to their camera and scanner counterparts. High-fidelity coverage of facilities like the PUREX tunnels require multiple forays and millions of images from thousands of vantages for covering acres of convoluted surfaces of interiors and contents. The surface area is high because the contents have intricate 3D geometry. Roving robots are preferred for their substantial range, payload capacity, and ability to loiter for imaging with low power expenditure. However, roving robots cannot get the bird's-eye views necessary for overflight of rail or reaching the heights over train cars, and they cannot handle the large vertical drops of H-Canyon. Despite other immense advantages and relevance, flying robots are challenged to deploy the larger payloads with long exposures since they are especially power-hungry when loitering in hover for radiation imaging.

Site inspection and monitoring is a critical application field and a sustaining need. Robots are ideal systems to conduct nuclear monitoring missions - for environmental protection, preventive inspection, and emergency response [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Such operations go as far back as Three Mile Island [3] and Chernobyl [1, 2]. A variety of robotic systems have been used, including unmanned aircraft [4, 7, 11, 13], ground vehicles [5, 6, 8, 9, 10, 12, 15, 16, 17, 18, 19, 20] or underwater systems [14, 21], each of them serving a different need. At Fukushima, it was only after days that a few robots managed to provide service, and it was much longer for effective results [13, 15, 16, 17].

For site inspection and monitoring of dry environments, both ground and aerial RadBots matter to exploit the advantages of each. Aerial robots provide a) rapid, remote access to narrow or human-inaccessible areas, b) versatility regarding the structures that can be accessed, inspected and mapped, c) comparatively large and rapid inspection coverage, and d) small size. On the other hand, ground robotics provide a) long–endurance operation, b) payload capabilities often critical for radiation sensing devices and other relevant sensors, c) power–efficiency during sensor measures that require long exposure, and d) advanced robustness in harsh environments.

TETHERING

The obvious benefit of untethered robotic systems is freedom of movement. These systems exhibit both agility and (depending on energy storage) great range. This allows for paths that are easier to plan, simple backtracking and advantages of roundabout routing. The absence of a tether reduces weight, volume and need for drawbar pull. Tetherless robots traverse rougher terrain. Tethers limit robot movement. Tether drag, whether advancing or recovering by pulling, quickly becomes untenable for a circuitous route. While there are path-planning systems available that take into account tether movement and obstacle interaction [22,23] they cannot overcome the physics of drag on a circuitous tethered route.

Tethers can fail. Tethers are subjected to damaging interactions. Wear from abrasion, debris and sharp surfaces, tangling, and catching have all led to tether and system failure.

Tethered robotic systems are ideal for use in straight-path, uncluttered environments where tethers don’t tangle or catch. Tethers have succeeded in tunnels, waste tanks and open floor areas. Line of sight operations are especially amenable for driving and egress or manual extraction should systems fail.

Early tethered systems succeeded at Three Mile Island and Chernobyl [24]. The vast majority of these dragged tethers. Exceptions include some Three Mile Island systems that reeled onboard to preclude dragging [3].

Tethering allows for longer operational duration than untethered systems. With tethering, power is only limited by supply power to the tether. This is typically less a concern than carrying sufficient onboard energy. However, docking and recharging as part of conops can substantially extend battery operations for untethered systems.

Strength members are usually integrated into tethers, providing possibility of mechanical recovery. Success depends more on a straight pull than on tether strength. Tethered systems typically provide more persistent communication and higher bandwidth that support video and teleoperated systems.

Some systems carry tether onboard and reel to unwind/wind tether to mitigate dragging issues [12][25]. The weight and volume of onboard tethering systems are substantial robot burdens. The ultimate cases for freedom from tether burden are robot drones, but all small robots are escalated in size and restricted in operation by tethers. Tethered systems that carry cable onboard to reduce dragging of the cable on the ground must carry the entire length of tether plus mechanisms to reel and manage. Even with this feature tethers have still snagged or caught on objects. In the Daiichi scenario, during one of the missions, a tether caught on piping, entrapped the robot and led to abandonment.

In addition to generic tether considerations, tethers in nuclear environments are vulnerable to contamination and become waste or exposure liabilities.

A Fukushima Daiichi deployment team found that wireless communication was not possible inside the facility even when resorting to specialty ultra high frequency channels. A 510 Packbot from iRobot, and the Quince system from Chiba Institute of Technology were deployed. Quince 1 was lost due to wireless communication loss in October 2011 but Quince 2 successfully completed a mission where one robot carried radiation meters, fisheye camera, and laser rangefinder (N-visage camera). The other robot acted as a communication relay to extend the operational range [26] Even with a consistent line of communication, the wireless comm exhibited less bandwidth than its tethered counterpart.

AUTONOMY

Remote systems have emerged for important roles, however, many essential operations are beyond the reach of conventional remote systems and human entries. Foremost among these is the need for robotically and autonomously acquiring, integrating and utilizing radiological, thermal, spatial and visual data of facilities that are too circuitous, too large, or too inaccessible by tether. Technologies to preclude tethering include localization, perception, navigation, safeguarding and task prescription.

Self–localization is essential in GPS–denied, narrow, cluttered, dark or reflective environments. Simultaneously, RadBots must derive, in real–time, selectively high–fidelity 3D reconstructions of their surroundings and further fuse these with radiation and heat maps. Semantic classification enhances these maps to enrich a RadBots’ understanding and ability to explore the world. Probabilistic approaches support robotic belief, confidence and mapping fidelity. The derived multimodal maps allow systematic assessment of nuclear sites.

Gamma radiation cameras like SRNL’s GrayQb, Canberra’s iPIX, and Createc’s N-Visage image radiation intensities using phosphor storage plates, CMOS sensors, and CZT detectors, respectively. When resulting images are fused with other sensing modes such as visual images and LiDAR, the location and intensities of radiation hotspots can be estimated. Though these radiation sensors exist, little research has been done on how to incorporate them effectively in an autonomous robotic context. The prospects for success are great. These radiation cameras acquire images that are amenable to fusion and modeling, but their deployment and determination of location and pointing is currently by human workers. Robots are superb at deploying and determining location and pointing of such cameras.

The considerations of exposure settings and imaging dwell time for radiation cameras are critical. These are determined from the expected strength of the field to be imaged, and dwell time can often be on the order of minutes or hours. And if the location and strength of a field is unknown, that requires adaptation and tuning of settings and dwell times during deployment. In the multimodal characterization of unknown nuclear facilities where radiation is of utmost interest, the aforementioned considerations of source localization, field strength estimation, radiation camera exposure settings, and dwell time are unique new issues to robotic state-of-art. These affect operation when considering resource constraints such as time, mobility, and energy.

Fig. 3. To test multimodal mapping in cold facilities, UV light and UV fluorescent paint are used as surrogates for visually sensing pseudo-contamination and testing algorithms. The phenomenon can be viewed with a standard camera to provide an economical sensing mode analogous to radiation imaging. The image shows a train car sprayed with UV fluorescent paint, with natural light (visual image) on the left and UV light (radiation image) on the right. This is symbolic of a train car in a waste management tunnel as viewed by a radiation camera.

Robots have been used to autonomously characterize environments visually, geometrically, and thermally. However, radiation mapping poses new challenges to path planning, probabilistic mapping, and resource allocation. To begin developing the robotic capabilities required to integrate radiation imaging, UV fluorescent paint that is transparent in natural light but fluorescent in UV light is taken as an analogue to radiation. The robots project UV light into an analog environment and image the resulting fluorescence to be interpreted as analogs to data resulting from actual radiation sensing. This can be seen in Fig. 3. Visual, range and thermal sensors are actuals.

New capabilities for coupling perception uncertainties and semantic detections plan in order to achieve semantically–enhanced active perception that also accounts for nuclear–relevant sensing modalities for autonomous exploration and inspection. Comprehensive coverage at the required resolutions and dwell times are achieved, while robots conduct inspection missions like tunnel mapping.

New models and methods significantly increase the robustness of autonomous flying and roving robots in challenging environments. Novel methods for online 3D uncertainty model characterization enable safe and adaptive operation in inspection domains that were hitherto inaccessible due to prohibitive assumptions on the sufficiency and variability of information sources.

State–of–the–art LiDAR–based methods create quality 3D maps sufficient for many inspection tasks. For nuclear relevance, these must fuse visual, radiation and heat estimates with the LiDAR to create multimodal maps. The geometric accuracy, fidelity and multimodality of these unified maps enable systematic characterization of a nuclear facility.

The capability of comprehensive data collection in hard to reach and dangerous locations with small, tetherless ground and aerial robots has the potential to generalize and economize many operations. Additionally, RadBots can improve routine monitoring tasks, and multimodal 3D models provide a quantified record to monitor changes over time.

CONTEXT AND ANALOG: PUREX TUNNEL 1

Hanford's PUREX Tunnel 1 serves as a context for discussing and illustrating automation for exploratory inspection. It is a wooden tunnel where nuclear waste is stored on train cars. Radiation levels preclude humans. PUREX Tunnel 1 is built with creosoted timbers whose state and lifetime are not fully known. That is in part because timber strength degrades with gamma exposure over time [27]. The interior has not been viewed in the decades since sealing the tunnel doors. There has been no compelling motivation or practical means of entry, and remote operations of this type defied early robotic state-of-art. The technology base now exists to robotically characterize PUREX Tunnel 1 for high-fidelity evaluation of tunnel state and lifetime. Such characterization would inform projections, risk mitigations and strategies. Figure 4 is a 3D model from records of PUREX 1 that is used to understand goals and constraints for robotic inspection. Long, straight alley-ways between the train cars and tunnel walls form flat-floored corridor that is navigable by tethered or tetherless ground robots.

As analogy, and to illustrate the technologies in action, a coalmine tunnel with tracks and mine cars is robotically modeled. Figure 5 is an image of a tetherless robot in the coalmine. Figure 6 shows multimodal modeling of the mine. The top left is a visual image, bottom left is a thermal image, and a point cloud collected by LiDAR is on the right. Autonomous exploration of this nature is within state-of-art and possible with or without tether. Even wall-following and waypoint following prescriptions for driving in narrow corridors succeed in facilities like this.

Fig. 4. A 3D model was constructed based on DOE documentation of PUREX Tunnel 1, showing eight train cars loaded with hot waste. Walls and ceiling are removed for viewing.

Fig. 5. A tetherless robot forays beside a train car. This is akin to driving on the floor between train cars and walls in PUREX Tunnel 1.

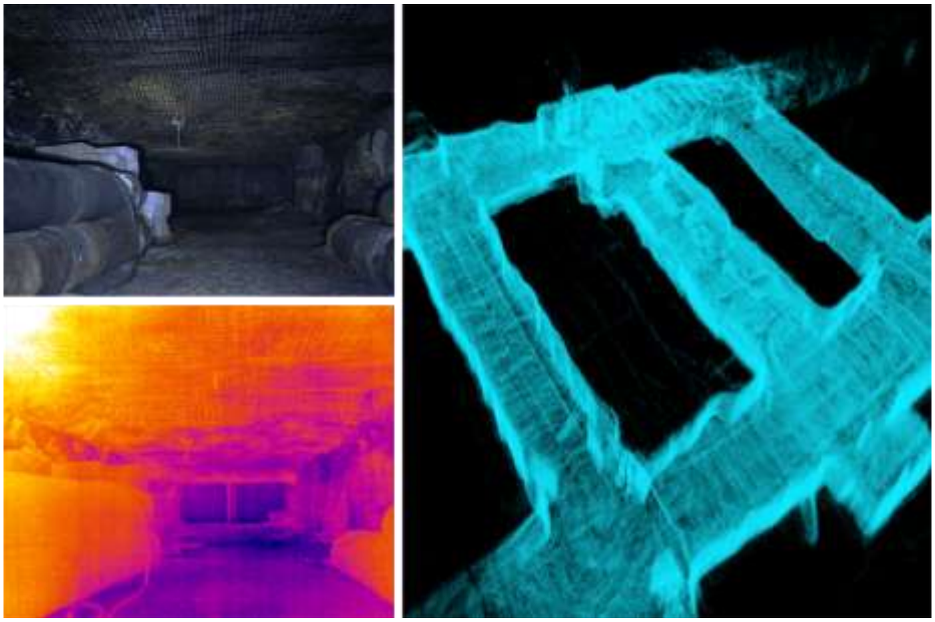

Fig. 6. Multimodal sensing including visual (top left), thermal (bottom left), and LiDAR mapping (right) is shown for a mine tunnel akin to PUREX.

CONCLUSION

Developments in perception, localization, navigation, safeguarding, planning and mapping enable tetherless inspection and multimodal modeling of nuclear facilities.

The automation technologies that enable tetherless operations are also valued augmentation to tethered operations. Augmentations take the form of advisories, automated data acquisition, model-as-you-go, and virtual presence that greatly enhance any operation.

Requisite automation technologies for tetherless operation are state-of-art in robotics, but not yet embraced or infused in hot deployments. Some of that is sufficiency and favor of tethering and teleoperation where those work. Some of that is the barrier to technology adoption. Some of that is the readiness of tested, robust systems. These will be overcome when instances of compelling need, technical readiness and mobility constraint of tether compound to motivate implementation.

FUTURE

Future research would deepen capabilities for (1) multimodal sensing and semantic representation to achieve robust navigation, driving and flight, multimodal mapping, and semantic classification in cluttered, complex environments, (2) Active perception and semantically-enhanced exploration and inspection enabling intelligent behaviors when teleoperation is not feasible, and (3) System optimization and enhanced payloads with radiographic, and thermographic sensing.

The capability of multimodal, comprehensive data collection in hard to reach locations is essential in DOE facilities. Additionally, robots can reduce the risk and effort required to collect relevant information while keeping workers from harm. The ability to use sensor modalities beyond visible-light cameras to estimate robot pose will be valuable in visually degraded environments. Improving the speed, comprehensiveness, and cost-effectiveness of inspection and monitoring will equip practitioners and policy-makers with the information necessary to prioritize repair and remediation of facilities and sites in the nuclear complex.

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