Surface Robotics

Final Report

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Introduction

This study

Transport Canada engaged the Institute on Governance (IOG) to study surface robotics, that is, small vehicles that operate with some degree of autonomy on sidewalks in uncontrolled settings. This is contrasted with similar robots that operate in controlled environments such as warehouses or farm fields.

As Table 1 indicates, this relatively new technology, which is an application of artificial intelligence, is known by many names. For the purposes of the present report, they will be referred to as Micro Utility Devices (MUDs), or occasionally as surface robots (SRs) or autonomous ground vehicles (AGVs) with the understanding that reference is only to those SRs or AGVs that operate on public sidewalks.

Table 1: Terms used for small vehicles that travel with some degree of autonomy on public sidewalks
Generic Names
Automated or autonomous ground vehicles (AGVs)
Autonomous mobile robots or Mobile robots
Bots (robots)
Connected autonomous vehicles (CAVs)
Micro Utility Devices (MUDs)
Sidewalk robots
Surface robots
Specialized application names
Autonomous delivery robots, Delivery robots or Delivery Bots
Autonomous snow removal
Personal delivery vehicles (PDVs)
Sidewalk inspection robots

The project comprises:

1. Consultation with experts and stakeholders (see Appendix 1);
2. A discussion paper about the technology, its applications, and the emerging industry;
3. Workshops with stakeholders to discuss issues using the discussion paper as a starting point; and
4. This final report.

The project builds on the work of Dr. Shauna Brail and Dr. Betsy Donald who authored *Robotic Cargo Transport* (2021) for Transport Canada.

Technology companies in Canada, the United States, and Europe are developing and testing automated ground vehicles. These consist of the wheeled (or tracked) vehicle itself and an electric motor powered by rechargeable batteries.

Onboard are advanced technologies such as sensors including cameras, lidars and/or radars, and computers with AI programming to enable processing of the sensor inputs and control of the operation of the robot. At this early stage, the technology is at a low level of maturity because its sensors and AI programming cannot fully distinguish between humans and other objects on the sidewalk and are not yet fully able to operate effectively outside of a narrow range of weather. MUDs are equipped with two-way communication to a base station where a human operator intervenes in the control of the robot as necessary. This also offers the potential for two-way communication between people near the MUD and the base station operator. During this early phase, MUDs are usually accompanied by human chaperones while deployed on sidewalks. In other words, these small machines, though referred to as *autonomous*, have limited autonomy at present.

The primary market opportunity for these devices is the “last mile” of services – which is often the most expensive part of the delivery journey for goods. If deployed in urban or suburban areas, MUDs operate on sidewalks, entering roads only to cross them. Pilot projects using this technology are often limited to suburban neighborhoods or campuses where there is low sidewalk traffic and well-defined, stable conditions. Some pilot projects have brought them into more congested areas of large cities which has raised concerns of citizens and, as a result, of municipal politicians.

This study reviews the state of the technology of these devices, their use in Canada, and their social impacts. Synthesizing the results of research and consultations, the report concludes with recommendations to address concerns and guide the next stages of development.

The issue

A primary rationale for pursuing this emerging technology is the potential, when mature and much closer to full autonomy, to reduce costs and environmental impacts as compared to incumbent human-operated “last mile” service provision. Surface robots are an early-stage technology and their use in cities in Canada and the United States has raised questions about how they interact with humans, especially persons with disabilities, and pets on sidewalks. As a new technology, the question arises what are the next steps and what can Transport Canada and agencies at all levels of government do to further its development in a way that meets safety, cost, and legal concerns?

Scope

This study focuses on MUDs used in uncontrolled settings out-of-doors where they will interact with the busy sidewalk landscape. In fact, there are a great many potential applications for this technology as listed in Table 2. However, excluded from the scope of the project are vehicles primarily intended for road use, aerial drones, and robots used in controlled indoor settings such as large fulfilment or logistical centers. Some of the issues examined here may have applications in less-controlled indoor settings such as shopping malls.

Table 2: Possible applications for automated ground vehicles
• Airports: transport luggage to and from aircraft
• Construction sites: deliver tools, materials, hardware
• Hospital campuses: deliver prescriptions, test samples, portable medical equipment
• Municipal infrastructure: inspect sidewalks, asphalt paving
• Non-wheeled, "legged" robots that could operate in more complex environments such as oil rigs that require climbing stairs
• Offices: deliver mail, parcels, couriered documents, office supplies
• Residential: deliver mail, e-commerce parcels, groceries, meals
• Security: patrol fences, buildings, campuses
• University campuses: deliver vending snacks, books, documents

This paper, first, reviews the technologies that underpin MUDs, their maturity and remaining technological challenges. Second, it discusses the sector's nascent technological ecosystem in Canada and the potential for market growth. Finally, it explores social impacts, safety, regulatory, legal, and ethical implications for this new technology.

Approach

The approach taken for this study combined online research of journals, industry press, government reports and those of other organizations with a series of interviews, and two workshops with approximately thirty people from the MUD industry, university researchers, technology experts, municipal and provincial government officials, members of the accessibility community, and Transport Canada. Views of individuals consulted are not attributed and are summarized in boxes throughout the report, titled "Findings about…" and these are also captured in Appendix 3.

An early finding of the study was the degree to which the technology is at a low level of maturity. The approach has been to find out what needs to be done and how, to advance the technology's maturity and to meet the concerns of citizens about surface robotics.

The technology and its applications

Emergence of AI and robotics

The advancement of artificial intelligence (AI), which is computationally intensive, has benefitted from the increase in and lower cost of computational power that has characterized computer development in recent decades. These advances are evident in the nascent field of surface robotics which is built around AI processing of sensory inputs. It is increasingly possible and relatively inexpensive to create the AI programs that process inputs from cameras and other sensors enabling a robot to move semi-autonomously or autonomously in an effective manner.

Figure 1 Dianomix robot on suburban sidewalk

Source : https://dianomix.com

Technological components of MUDs are listed in Table 3. At present, these robots represent a simple, practical application of off-the-shelf technology with some additional development and customization. Additional optional equipment for operation in the public domain includes temperature-controlled storage (e.g., cooling for groceries, warming for meal orders), use of robotically controlled arms for delivery, blades to plow snow, and mower blades to cut grass.

Table 3: Technological components of MUDs
***Sensors**:* cameras (visual spectrum, infra-red), radars, lidars, microphones, lasers, and accelerometers
***Processors**:* high-powered computers with AI programming such as neural networks to process inputs from sensors to “intelligently” guide the vehicle. The computer and its AI “stack” is on the vehicle.
***Power**:* electric motors powered by rechargeable batteries
***Controllers, communications**:* controllers for steering and other functions of the vehicle[1] and wireless communications usually based on 5G cellular networks
***Safety**:* warning lights, sounds, and two-way audio communication with base station operator

[1] Many robots will have hybrid management with an onboard computer making most of the decisions while a remote human operator monitors it, overriding when necessary.

A rapidly emerging but not yet "mature" technology

Gill Pratt, former Program Manager at the U.S. Defense Advanced Research Projects Agency (DARPA) has written about the coming "Cambrian Explosion" in (all) robotics as a virtuous cycle of explosive growth results from developments in many component technologies including computing, data storage, and communications (Pratt 2015, 51-60). Pratt notes that these base technologies could be significantly levered by deep learning and cloud robotics. Deep learning permits robots to develop vast sets of generalized associations enabling robots to recognize speech and interpret images.

Through cloud computing, robots can share each other's data to improve their ability to identify sidewalks, children, adults, people in wheelchairs or using walkers, bicycles, or a football that rolls into their path. As the number of robots involved grows, their ability to identify objects will greatly improve. This would begin to address the shortcoming of AI noted by Du et al (2019) that, "classical algorithms are insufficient for safe [autonomous] navigation around pedestrians and remaining on the sidewalk space."

Further into the future, Pratt (2015, 55-57) identifies four Big Ideas related to cloud robotics that may emerge. These will not necessarily all be relevant for MUDs, but they provide an indication of possible directions for the technology:

- Memory-based autonomy: ability of computers to solve problems based on memories of previous circumstances;
- High-speed sharing of experiences: robots learning from each other;
- Learning from imagination: using simulation to explore circumstances that might be faced by a robot later and to experiment with solutions; and
- Learning from people: overcome the weakness of robots in perception using massive visual databases.

Technological maturity

In 2018, SAE International (formerly the Society of Automotive Engineers) proposed standard J3016TM, "Levels of Driving Automation", with levels zero to five indicating increasing levels of automation and commensurate decreasing need for human input (SAE 2018). These have been adapted by EarthSense, with support from the U.S. Department of Energy and ARPA-E for application to surface robots used in agricultural applications (EarthSense 2021). Agricultural applications are beyond the scope of the current project; like automated ground vehicles used in warehouses, they operate within a relatively controlled environment and do not interact with the general public. However, the taxonomy of technological maturity levels (TMLs) developed by EarthSense applies well to MUDs in the public domain and it is shown here, in Table 4. The full taxonomy is provided in Appendix A2. This scale can be used when considering the state and evolution of MUDs in Canada. It was the consensus of those consulted for this study that MUDs in use in Canada are at a level of maturity between 1 and 2.

Table 4: Levels of Autonomy for Field Robots

Level	Description	Time between interventions
0	Full manual teleoperation	N/A
1	Robot within line of sight (Hands off)	5 minutes
2	Operator on site or nearby (Eyes off)	1 hour
3	One operator oversees many robots (Mind off)	8 hours
4	Supervisor not on site (Monitoring off)	3 days
5	Robots adapt and improve execution (development: off)	extended operation

Future directions of the technology

The noted decrease in computing costs accompanies a decline in the cost of many sensors and related electronics. The smart phone revolution of the last decade has benefited surface robotics as it led to the mass production of smaller sensors and at much lower cost.

Future technological developments could add to the list of basic technical components listed in Table 3, perhaps in the form of new and better sensors or in the form of better approaches to processing of sensor inputs. There could also be new add-on components to provide for new applications of the robots.

Quantum computing, still in its infancy, may play a role in making AI more effective and efficient in years to come. This leading-edge technology could improve sidewalk navigation by improving the processing of sensor inputs and reducing latency (reaction times). Other current and future developments pertinent to surface robotics include massively parallel computing, biologically based computers, and advancements in wireless communication and cloud computing.

Technological challenges

There are technological challenges that need to be addressed to raise the technology maturity level of surface robots in Canada:

- Latency: the reaction time from observation through a camera or sensor to response action by the robot, regardless of whether the response, in whole or part, involves an operator at a base station. At present, latency is measured in thousandths of a second (milliseconds). Fully onboard, autonomous latency, in the future, will likely be in millionths of a second (microseconds).

- Vision and sensing in inclement conditions such as in snow, a rainstorm, dust cloud, or in bright sunlight.

- Extreme heat and cold may also affect sensors and cameras. At present, when these issues interfere with surface robot operations the solution is to suspend the robot's operation and/or to depend more heavily on remote or on-site human overseers.

- Communicating, especially with persons with disabilities including the blind or deaf, the elderly, and children. This is a computational challenge as well as one of integration of insights from these communities in the design and functioning of MUDs.

Findings about the technology
1. Most of the technologies needed to make surface robots are available but there is still a need for improvements including better access to more advanced artificial intelligence, cloud computing, and development of common image and sensor databases to improve the ability of neural networks to "recognize" objects.
2. The roadblocks to surface robotics are not mainly technological. They are driven by issues of social acceptance and adapting MUDs to meet the needs of communities they may serve while addressing citizen concerns.

The industry ecosystem and economics of surface robotics

Industry ecosystem and the opportunity for collaboration

The MUD industrial ecosystem in Canada is small and young, with potential for sustainable growth with the right collaborations. There are at least three Canadian-based surface robotics companies that have pilot operations in Canada: Dianomix, Swap Robotics, and Tiny Mile. These companies are small when compared to firms outside Canada, such as Starship, that are backed by significant financial resources. Some large fulfilment and delivery companies including Amazon, Purolator, and DHL (DHL 2022) are also working on their own solutions.

Canada's autonomous *road vehicle* market is much larger than the *sidewalk robot* market, and autonomous road vehicles are entering a landscape with a safety and regulatory framework that is based on human driven vehicles. There is overlap in some of the technologies used in the MUD industry and in the autonomous road vehicle industries such as in sensors, and AI processing (e.g., neural networks). There are extensive industry and technological ecosystems of companies in the Ottawa and Waterloo regions and others working toward on-road, autonomous vehicles, including major motor vehicle manufacturers as well as specialized technology companies and suppliers.

In recent years, the Government of Canada has provided significant support to advance AI research, including creation of the Pan-Canadian Artificial Intelligence Strategy (CIFAR, 2021). Under the strategy, three research institutes in Edmonton, Toronto, and Montreal have received federal funding. Mila, in Montreal, conducts extensive fundamental and applied research in a wide variety of AI sub-fields focused on machine learning. The federal government also created an industry-led AI supercluster, Scale AI, that funds research in a range of AI areas. This research could have application in automated ground vehicles including MUDs.

Innovation policy scholarship and experience demonstrate potential benefits to emerging technology-based industries of pre-competitive research by consortia of companies and researchers. In the case of the automated technologies used by MUDs, a consortium could help the technology reach higher levels of maturity more quickly than if the Canadian companies were to move ahead without such collaboration.

Adopting an approach such as constructive technology assessment (see Box 1) could provide the opportunity to explore issues related to social acceptance as well as law and regulation. Through collaboration it will be possible to further the maturation of the technology by bringing together the technology developers with users and others impacted by the technology to have positive impact on public acceptance.

Box 1: Constructive Technology Assessment

"The core idea of constructive technology assessment (CTA) is that the social problems surrounding technology can and must be addressed through the inclusion of a large diversity of actors in technological design and implementation processes, including especially social actors."

From Encyclopedia.com

Economics of autonomous systems

Brail and Donald (2021) found that the "benefits of autonomous delivery include the potential for reduced costs, contactless delivery, improved equity, safety, and decarbonization" (Brail and Donald, 2021, 6). They termed their own review of the economics of robotic delivery as "inconclusive" yet there are compelling reasons to pursue further research in anticipation of such benefits. There may be a significant cost advantage for robots delivering services in low density suburban areas, if a more mature and more autonomous technology could achieve a higher degree of public acceptance.

More mature MUDs could improve the lives of seniors by raising the level of service they could receive *in their homes* at relatively low cost. Benefits may also include a reduced environmental impact of delivery services.

Findings about the industry ecosystem
1. Canadian companies that make MUDs are developing the technology independently of each other. Mainly they use off-the-shelf component technology, and their innovation is in putting these together and making them work well.
2. The industry in Canada is so small and new, it may be premature to think in terms of an industry ecosystem at present; rather, a policy objective might be working toward building one, and linking it to existing ecosystems for AI and autonomous road vehicles.
3. Conversations with stakeholders indicated a willingness to explore better connections (strengthening the industry ecosystem) particularly with the AI research community as well as with communities that have concerns, including the accessibility community.

Social impacts, public acceptance, and privacy

The introduction of sidewalk robots raises three related areas of social concern:

- Safety, including how MUDs interact with persons with disabilities;
- Privacy; and
- Displacement of workers.

Figure 2 Tiny Mile's robots have operated in Toronto for over a year but were recently pulled from the streets. (Source: https://tinymile.ai)

Public acceptance and safety

Brail and Donald (2021) found that the "technological development for autonomous cargo delivery is moving faster than the policy environment." The introduction of MUDs onto city sidewalks across North America has come, in most cases, with limited or no advance engagement of the public to offer the opportunity to air concerns and to raise awareness about the potential of this new technology. Often, these robots appear as a surprise to residents navigating the streets of their neighborhoods. Such a surprise presents an example of Collingridge's dilemma (1980): in the early stages of a new technological system there is limited knowledge of the consequences and potential hazards of that technology that make it difficult to win public support.

A case in point is the action taken in three cities – Ottawa, Toronto, and San Francisco – to suspend the use of MUDs from their sidewalks. These decisions were driven by concerns about pedestrian safety, particularly for persons with disabilities. The unexpected introduction of MUDs raised concerns about how they will interact when they come into the path of an elderly person, a pet, or someone using a wheelchair, as well concerns about MUDs adding to the congestion of already busy sidewalks. In all three cities, officials expressed the need for time to allow policy to catch up to the technology and for the technology itself to mature.

The second half of Collingridge's Dilemma addresses the introduction of a new technology that uses an older infrastructure. It says that "well-established technological systems have a high degree of user knowledge and comfort." When this happens, as is the case here with MUDs, a cost is imposed on existing users and uses of sidewalk infrastructure. There is a need to work out new ways of working, new rules, new procedures, and even new etiquette. Proponents of the new technology need to build their case for this new, additional use, and for its interaction with existing uses and users.

In some applications MUDs may be able to address the very issues for which they are receiving criticism, namely, helping seniors and persons with disabilities.

Low-density suburban areas in Canadian cities receive, typically, a lower level of snow clearance services than the more densely inhabited ones. Automated devices equipped with snowplows could provide a cost-effective solution to increasing the level of service thus improving sidewalk accessibility. Also, MUDs used as delivery vehicles, their main use at present, can benefit those unable to leave their homes because of poor mobility. However, to mount a successful argument for the introduction of sidewalk robots, producers and regulators must demonstrate that they are listening to members of society who have reservations about this new technology.

It is noteworthy that the concept of *inclusive innovation* (see Box 2) addresses how to include those often left out of the process of innovation but who are among the first to be affected by it. In the case of MUDs, those concerned about accessibility issues would like to have the opportunity to provide input directly to those developing and using the technology. As a participant of one of this project's roundtables put it, it is important to not "treat [disabled persons] like outliers, and not part of our communities."

Box 2: Inclusive Innovation

The specific phrase was coined in a World Bank report in 2007. The term describes the inclusive pursuit of innovation that has social (and environmental) aims that addresses target communities and local context.

From Inclusive Innovation Learning and Stories Lab

A final point related to safety raised by contributors to this study is the potential to re-imagine the transportation paradigm. Several contributors encouraged a re-think of road use over the longer term. They suggest that Canadian roads and sidewalks are becoming increasingly cluttered, and devices like e-scooters, bicycles and now MUDs represent a new category of transportation that is neither motor vehicle nor pedestrian. Participants suggested that it may be time to re-consider road design in Canada and introduce a "third lane" separate from motor vehicle lanes and pedestrian sidewalks.

Privacy and other legal issues

There are concerns about the possible impact of MUDs on privacy and officials in the three cities mentioned above have raised privacy concerns. Sidewalk robots have cameras or other sensors which can potentially record images and sounds around the vehicle. This raises questions such as, Who can access this content? Where is the data stored? For how long? Does the human operator have a duty to report crimes captured on a MUD camera? In researching this study, little material was found on the matter of MUDs and privacy.

Other legal concerns include liability and insurance. What happens if and when someone is injured by a MUD? Further, what amount of insurance are operators of MUDs able to access and is this enough? Legal precedents would have to rely on cases involving older technologies. All of these legal questions need further study with a view to understanding how current laws apply to the use of this new technology.

Labour market impacts

Displacement of workers is another social impact for consideration. A recent submission to the Subcommittee on Consumer Protection and Commerce of the United States Congress, addressed issues raised by automation of transportation technologies writ large. In their submission the AFL-CIO, a federation of unions representing over 12.5 million workers, raised concerns related to safety and the lack of standards and regulatory framework. These unions are concerned about the displacement of workers by technology, and whether they will be "'reabsorbed' into jobs with similar income and workplace protections" (AFL-CIO 2021, 2-3). The AFL-CIO proposed that the U.S. federal government undertake workforce impact assessments involving both workers and frontline management (Ibid., 4)

Findings about public acceptance, safety, and privacy
On public acceptance
1. Opposition to surface robots can be exacerbated by a lack of information. Companies and jurisdictions introducing MUDs need to undertake a vigorous awareness-raising effort to alert the population to their introduction and how they will operate and interact with sidewalk users. Better efforts to engage interested and affected parties will be important in helping to decide how the technology is developed and how it is used in what are likely to be a wide range of applications.
2. Establishing standards for safety and best practice human-robot interface design, in consultation with the accessibility community, would go a long way to reassuring those with concerns about the technology.
On privacy and other legal issues
3. Further research is required to determine the full extent of existing and emerging privacy concerns and of other legal issues arising from the use of MUDs in Canadian cities.

Standards and regulations

While MUDs are novel, their underlying technologies are borrowed from what already exists in other forms. They are assembled in a new way and, when put to use, enter a new physical space. This space has existing rules, regulations, and common practices. There may be a need for new rules and regulations. Indeed, an approach known as Anticipatory Regulation could be useful.

Anticipatory regulation allows a regulatory body or bodies, working in collaboration, to establish an "overall framework with a workable scope"

(Brévignon-Dodin 2006). In the case of surface robots, a regulatory body could draw from regulations and safety standards that apply to similar types of vehicles or machines to create a new, single framework. Building upon existing standards, regulations and legislation avoids duplication; the new standard would be adapted to specific features that may emerge as the technology matures. The framework creates the opportunity for pooling of expertise and the development of requirements that keep pace with the technology.

In the United States, the AFL-CIO suggested that the U.S. Department of Transportation increase the coverage of Federal Motor Vehicle Safety Standards (FMVSS) to cover automated vehicles including what it refers to as “bots” and delivery vehicles. It suggested that “these vehicles should also be subjected to proper federal scrutiny and safety requirements” (AFL-CIO 2021, 6). Perhaps, they suggest, there should be “a new federal operating authority for bots and delivery vehicles. They also note that a vehicle that is being used solely for commercial purposes must be required to carry a minimum level of insurance in case of a crash and demonstrate a comprehensive maintenance plan that accounts for the heavy wear and tear it will undergo as a part of continuous commercial operations” (AFL-CIO 2021, 6).

Findings about standards and regulations
1. In Canada, regulation of the *use* of surface robots is in the jurisdiction of provincial and municipal governments. To date, governments of Ontario, Alberta and Manitoba are aware of this issue. They need to establish guidelines, in the short term, and regulations and laws as the technology matures over the longer term.
2. Transport Canada regulates the design and manufacture of road vehicles, including safety standards. This approach could be extended to MUDs, although this may require new legislation.
3. Members of the accessibility community identified several requirements that, if implemented, would address their major concerns. These are listed in the Conclusion.

Conclusion

This study has shown that MUDs may offer new and improved functionality and may do so with substantial cost savings. However, at present, the technology is immature, the markets for it are relatively undeveloped, and there are social concerns with respect to the technology. MUDs currently are ranked at the lowest levels of technological maturity, which means they are far from full autonomy and continue to require human supervision and intervention. Higher maturity levels would see ever increasing degrees of autonomous operation until, sometime in the future, they could in principle operate with almost complete autonomy, although connection to a remote human overseer is likely to continue. The economics of the technology depends on achieving greater autonomy, which will bring down the per-kilometer cost and make possible their use in more and varied applications.

Box 3: Serving Canadians

- A universal sound to identify an approaching robot, activated only when it comes within a certain distance of a human (e.g., two meters), to limit noise pollution
- A maximum speed limit, automatically adjusted for congestion levels
- A single reporting mechanism and data library that is easy to access and provides for uploading and sharing of incident reports (see section on *Pooling of R&D*)
- A requirement that MUDs yield to humans in their path – this is currently the default but should be formalized
- A universal interface, operated by multiple modalities to accommodate a very wide range of abilities including for persons who are blind and/or deaf.

Further work is needed to increase the level of maturity of surface robotics. That the cities of Toronto, Ottawa and San Francisco have suspended their use is indicative that MUDs are not fully ready for real world conditions in several respects. This includes the ability to fully accommodate normal sidewalk traffic safely and accommodate the needs of persons with disabilities in an equitable manner.

Box 4: Selected organizations with interests in automated vehicle safety

CCMTA Canadian Council of Motor Vehicle Transport Administrators Working Group on Autonomous Vehicles

AAMVA American Association of Motor Vehicle Administrators Automated Vehicles Subcommittee

SAE International Automated Vehicle Safety Consortium (AVSC)

There are strategies that could be followed to improve the sharing of data and technology which might accelerate the maturation of the MUDs. The federal government in Canada is investing a great deal on a strategy for the development of artificial intelligence yet companies that make MUDs in Canada have little or no connection with this activity.

Promote safety and accessibility for all

The *Accessible Canada Act* (2019) envisions a Canada without barriers, where all Canadians with a physical or cognitive disability are supported. Proponents of autonomous robotic technology need to consult the accessibility community in Canada to ensure that MUDs deployed in Canadian public spaces do not create new barriers but, rather, augment the living experience of all Canadians. Companies that build MUDs have attempted to consider the needs of Canada's diverse population in the design of all MUDs but more direct consultation is needed. Box 3 lists some of the safety features members of the accessibility community would like to see included on MUDs.

Standards

It is normal, when a new technology emerges, that the development of standards is key to that technology's safe and widespread adoption. In this study, several standards were mentioned as being relevant to surface robotics derived from other domains and organizations including CTMTA, IEEE and SAE International for areas such as motor vehicles and highway safety. Box 4 lists three leading organizations that are leading work on standards setting for autonomous vehicles, in general, including MUDs.

Box 5: What geospatial data could be recorded and shared?

- Sidewalk mapping
- Sidewalk faults and inconsistencies
- Signage and regulations (e.g., parking)
- Accessibility (e.g., curb cuts)
- What areas could be geofenced to promote safety?
  - High pedestrian traffic
  - Construction of roads, sidewalks, sidewalk repair underway

Pooling of R&D

The ability to pool some research and development (R&D) efforts could serve to advance this nascent sector more rapidly. In other industries companies involved in the development of complex technology have come together to collaborate at a pre-competitive level and, later, gone on to compete based on that cooperative work. Surface robotics companies, in cooperation with Transport Canada and perhaps provincial and municipal governments, might consider such an approach. Some of the activities that a pre-competitive surface robotics consortium could support include:

1. Pooling of geolocational data including images and mapping of sidewalks as well as providing for incident reporting (see Box 5).

2. Tapping advanced AI being developed in Canada with a view to accessing more powerful algorithms, neural network technology, etc. Also, a great deal of R&D is taking place in Canada with respect to *on-road* autonomous vehicles. This too might be an area to tap for technology related to sensors, data processing, training of AI systems (e.g., object recognition), etc. Finally, technology developed for MUDs in *controlled* conditions such as for warehouse use or farming could provide lessons learned that are applicable to MUDs used in the *uncontrolled* environment of urban sidewalks.

3. Developing a common approach to addressing the needs of the accessibility community, with a view to establishing design parameters to meet their needs including shape and coloring, warning sounds, lights and flags, etc. This could feed into standards development (see item 5 below).

4. Developing the technology and protocols to enable robots to communicate with each other and manage robot sidewalk traffic *across all companies*. It could be the objective to ensure that, as the number of robots on Canadian sidewalks increases, they would not "bunch up" and thus interfere with pedestrians. Related to this and to item 1 above would be the creation of geofencing to keep robots away from congested areas (e.g., during rush hour), where there is construction underway, or where there is an accident in progress.

5. Contributing to the development of standards such as the new ISO 4448 being developed by the Urban Robotics Foundation and integrating into the best practices for the industry the relevant parts of other standards such as those listed in Box 6.

Box 6: Standards relevant to surface robotics
ISO 4448 Ground-based automated mobility (under development)
ISO 26262 automotive-specific international standard that focuses on safety critical components
CSA B651 Accessible Design for the Built Environment
United Nations Regulation No. 138 re wheeled vehicles, equipment, and parts
SAE Ground Vehicle Lighting Standards Manual

Further research required

Several areas of concern and questions raised during this study went beyond the areas of expertise of those consulted. They require further investigation:

- How will data and images captured by MUDs be stored and used?
- Who has access to this data, and can it be summoned by a third party in the event of legal wrongdoing?

In summary

Surface robotic technology uses artificial intelligence to make it possible for sidewalk vehicles to operate, at present, with a little autonomy but in the future, with a higher degree of autonomy. Greater autonomy will make it possible to increase the level of various services to low density urban areas and to do so at relatively low cost and with reduced environmental impact. The technology can also benefit those with limited mobility by providing delivery and other services to their front doors.

Before that can happen, developers of the technology in concert with communities who are affected by these vehicles' travel on sidewalks must work together to establish operational protocols and procedures to ensure that all members of the public are protected.

There is potential for the industry to gain a technological step up by cooperating at a precompetitive level and by accessing the results of significant efforts to further the development of artificial intelligence in Canada in fields such as neural network technology. Cooperation could also lead to a pooling of geolocational data as well as cooperation on the development and application of standards. The path to the future is clear: it is one of cooperation and collaboration.

Implementation Plan

Specific steps that can be taken to implement the findings of this report.

MUD Action Plan

Item	Responsible	Activity & Timeline	Comments
Standards setting - Engage and support ISO 4448	Transport Canada (TC) (lead) with provincial and municipal governments	Collaboration 2-3 years	This activity is currently being undertaken by volunteers. Support would accelerate the completion and adoption of the standard.
Policy and thought leadership for MUDs	Transport Canada	Convening 5 years or more	In the same way that TC provides leadership and guidance for motor vehicles for standard safety features, it should do the same for MUDs. TC to investigate whether this will entail the introduction of legislation and/or what options could be followed for implementation between all levels of government.
Pre-competitive research and technology development and access to AI research	Transport Canada	Support 5 years or more	Federal government to support a pre-competitive consortium for the sharing of technology and access existing AI research. Consortium would be encouraged to interact with standards setting activities to contribute to standards development and adoption. Lead development areas: a) The use of cloud computing to store images and sensor data in common storage and use it to train neural networks in the recognition of objects b) Improved sensory technology (to operate in inclement weather, bright sunlight) c) Engage with the accessibility community in the development and adoption of standards and a common interface to meet their needs d) Development of common wireless communication standard to be used by all fleets to avoid congestion on sidewalks. (May be addressed as part of activities 1 or 2 above)

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A1: Appendix – People consulted

The content and views expressed in this report are solely those of the authors and cannot be attributed to any of those consulted, nor to Transport Canada. The authors and Transport Canada wish to thank those listed below for their time.

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Clearpath Robotics	Ryan Gariepy
Dianomix	Ali Asghari Marius Ulsamer
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A2: Appendix – Taxonomy of autonomy for field robots[2]

Developed by Girish Chowdhary, Co-founder and CTO, EarthSense, Inc., Associate Professor, Agricultural and Biological Engineering and Computer Science, UIUC, Chief Scientist, UIUC Center for Digital Agriculture Autonomous Farm[3], Associate Director AIFARMS National AI Institute.

Table 5: Maturity Levels (Autonomy) of Field Robots, used in agriculture
Level 1 Autonomy: A human needs to be always within line of sight of the robot. For example, in the agricultural automation system shown in the picture below, a human must always follow a robot as it goes through the field. Simple reactive tasks such as keeping the robot in the center of the row or spraying when a weed is detected are automated. A widely deployed example of autonomous systems at this level of autonomy are GPS guided tractors. Here, the human is required to be in the cab to take care of unforeseen events, but the tractor drives itself on pre-programmed paths.
Level 2 Autonomy: Now, the human operators switch to being (remote) supervisors: They don't have to follow the robot, the robot may be out of line of sight, but the human still must remain on the field and keep monitoring the robot in case it needs rescuing. This capability is an enabling-point for high-value applications in many industries. For example, at Level 2, an agricultural robot might be able to navigate a way-point prescribed path avoiding most obstacles, and only get stumped once in a while. The target time between interventions increases to about an hour. At this level of autonomy, the human may be able to do other tasks on the field, but likely only have one or two robots running autonomously under their supervision.
Level 3 Autonomy: In many industries, Level 3 autonomy represents an inflection point where large-scale deployments become quite attractive. A Level 3 robotic team is sufficiently capable of dealing with edge cases for several days so that a single human can monitor several robots. This is where most multi-robot-based farming systems begin to scale up. The human still might need to be on the field though to swap batteries, perform repairs, or rescue a stranded robot every so often.
Level 4 Autonomy: At level 4, autonomous robots can really be deployed at large scale, without being constrained by labor costs. Level 4 autonomous robot teams can deal with many of the edge cases themselves, becoming sufficiently autonomous so that the human doesn't feel the need to be on the field. They also have sufficient automated support infrastructure on-site. The

[2] https://www.earthsense.co/news/2020/7/24/levels-of-autonomy-for-field-robots

robots are capable of finding their base stations, get a new battery, perform minor repairs, and get out of difficult cases (perhaps with help from a remote human). This level of autonomy needs not only the on-robot software to mature, but the on-field infrastructure to automate and typically a reliable connection with remote users.
Level 5 Autonomy: At level 5, the robots begin to learn from their experience to improve operation beyond what the human designer has programmed in. They learn from each other, on site and from robot teams from other sites. They learn to predict how events affect their capabilities and plan proactively.

As an example of how human interaction with the system changes with increasing levels of autonomy, consider the following with the multi-robot agricultural autonomy example: At Level 3, the human on the field is responsible for organizing field activity if it is going to rain. At Level 4, the robot team uses data from the internet to determine when to go out based on the weather. At level 5, the robot team, anticipating that it’s going to rain tomorrow, learns to take care of tasks on the day before!

We have used an agricultural example, but the same could follow in other industries where precise control of the operating environment is not possible. For example, a disinfecting robot deployed at a hospital and operating at Level 3 could be monitored by a single person. At Level 4, teams of robots across multiple hospitals may be monitored through remote centers, while at Level 5, disinfecting robot teams would be able to predict human movements based on past patterns and proactively position themselves in areas where they expect high traffic.

We hope that this framework makes it easier to systematically analyze the readiness of the robots under consideration and helps achieve realistic deployment across industries in most field robotics applications. We believe that most autonomous robotic products will go through this maturity lifecycle. Here, we have tied the levels to actual deliverable product requirements in terms of human user interaction and not just to abstract statements like conditional automation or partial automation. This human-centric taxonomy is designed to overcome some of the criticism of the more abstract SAE levels of autonomy such as partial automation or conditional automation. Finally, by keeping the description of the levels of autonomy high-level and abstract, we aim to facilitate planning and decision-making across industries interested in adopting autonomous robots.

A3: Appendix – What We Heard

Technological maturity

- MUDs technology is not mature enough yet

Future directions of the technology

- The technology is in an early stage; much potential for the future

Technological challenges

- Collision avoidance is key
- Need to find the appropriate warning sound to alert blind people, especially, and everyone to the presence of a MUD – contrast this with the noise of trucks backing up which is highly disruptive at 2am
- MUDs should be able to respond to gestures
- Use “designing out” to incorporate the technology to address impacts as design for wide range of public – the way technology is designed is never the fault of those impacted [related to concept of design thinking which should be applied to MUDs]

Economics of autonomous systems

- Economics of AVs are attractive only with much higher degree of autonomy; accompanying MUDs with chaperones or even one-on-one remote operators is not economical
- There could be great benefits from MUDs in various activities, tasks, errands
- Use of MUDs in European airports has been successful
- Potentially huge positive utility

Social impacts, public acceptance, safety and privacy

- Space
  i) Delivery trucks compete for space but are not scrutinized – companies see parking tickets as a cost of doing business
  ii) As with e-scooters, use geo-fencing to limit MUDs to certain areas and exclude them, for example, from most congested areas
  iii) Need to enforce equal access
  iv) Cluttering [of sidewalks] a concern for frail people, guide dogs, blind people

- Design of infrastructure
  i) Have a third lane for scooters, mobility scooters – have equity

- Safety

i) Onus must be on the designers and operators to design and operate in a way compatible with the public, not on the public to adapt to MUDs
ii) MUDs need to be safe, reliable, easy to use, easy to interact with and unobstructive
iii) Need to demonstrate that robots can be trusted
iv) Remote control is not safe because of human complacency; continuous monitoring of is difficult for humans to do for long periods
v) Even a small robot travelling slowly could hurt a child, senior or pet
vi) Can't assume that people will get out of the way of a robot
vii) Right of way is cultural – need to have “pedestrian first” zones
viii) Delivery robots are helping people more than getting in the way
ix) Need for incident reporting and crash accountability
x) [Our] vehicles have travelled thousands of kilometres without a single incident
xi) When will it be safe to remove chaperones?

- Involvement of stakeholders
  i) Need to bring together stakeholders including technologists, blind people

- Other
  i) Boston is a good example of a framework for developers
  ii) PAVE Canada created to raise awareness of automated vehicles
  iii) Over the last 25 years, persons with disabilities have been helped greatly by technology. The problem is that technology that is poorly designed and implemented can hurt. Need more data collection about MUDs and their interactions with persons with disabilities.

Privacy and other legal issues
- People are wary of surveillance and data collection
- Privacy and other legal issues deserve separate study

Standards and regulations
- Need for uniformity
  i) Need uniformity of safety signals – lights, sounds, etc. – across MUDs made and run by different firms
  ii) Having a licensing system would be a huge advantage for improving safety
  iii) Example of National Building Code which is a federal standard that the provinces must meet or exceed
  iv) Avoid each municipality and province developing separate standards; speed, weight and aspect ratio (length to width to height) should be regulated along with emergency stop time and distance – this is especially important for connected autonomous vehicles

v) Need shape, size and colour standards, co-developed with persons with disabilities

- Warning standards
  i) Lights and sounds should be prescribed at the federal level to harmonize standards across the country
  ii) University College, London developed with industry a warning sound for scooters

- Process (of standards development)
  i) Build on existing regulations and standards
  ii) Need useability standards – not a lot of data on people with diverse abilities
  iii) People with disabilities not well-represented in development of the technology and standards for it
  iv) Start by regulating the indoor use of MUDs rather than start regulation development with outdoor MUDs [which is a more complicated regulation problem]
  v) Need a coherent process to establish rules but this will be a burden on smaller provinces [that have fewer resources to do such things]
  vi) Provincial regulations are too often merely in reaction; rather, need to pro-actively follow best practices
  vii) In California, due diligence is pushed to insurers
  viii) Need two types of licenses for operators and testers

- Operations
  i) Latency is a concern in terms of stopping distance, especially for vehicles with higher levels of autonomy and larger size
  ii) Latency is less of a concern for small vehicles travelling slowly

- General comments
  i) Delivery robots are helping people more than getting in the way
  ii) Robots should not contact people or impede the flow of [sidewalk] traffic.
  iii) Robots should get out of the way of deaf and blind people
  iv) Would be great if MUDs helped marginalized people; e.g., helping them around an airport
  v) Comparison of private, indoor setting vs public, outdoor setting; in the private setting, if a MUD impeded workers in some way it would be kicked out!
  vi) Uber poses the real regulator challenge

Pre-competitive R&D consortium

- Connection to federal AI efforts

i) There are very few Canadian companies, yet the federal government is investing in AI; need to bring in more voices
ii) Federal funding of AI is leading to Canada doing world-leading AI research with development of technologies useful for safety, edge cases – add to open-source library
iii) Need the researchers in AI and the industry to work together especially as these are early-stage technologies
iv) Implementers and designers need to work together

- Open-source libraries
  i) Consortium approach could be very good for the creation of open-source libraries including sidewalk specification data
  ii) Problem is everyone wants open-source access but does not want to contribute data; need to require contributions of data to gain access to the full database
  iii) A good role for the federal government would be to provide leadership for open-source libraries

- General
  i) Opportunity for a lot of win-win
  ii) Another good role for an R&D consortium would be for incident reporting
  iii) Canadian Robotics Council is bringing together government agencies, stakeholders, original equipment manufacturers. [Deals with much more than MUDs but includes MUDs]
  iv) In addition to R&D, the consortium could have important functions regarding:
    (1) Public awareness – how are MUDs a solution and to what problems
    (2) Capacity building
  v) Opportunity to support incubators