Preliminary Observations from Robot-enabled Surface Methane Concentration Monitoring at a MSW Landfill

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ABSTRACT: The use of robots for surface methane concentration (SMC) monitoring at municipal solid waste (MSW) landfills has the potential to improve quality of data acquisition for fugitive methane measurement over current practices. Methane concentrations vary significantly, both spatially and temporally, across a MSW landfill. However, current monitoring methods do not necessarily account for these significant spatial variations. A land-based robot coupled with commercially-available, relatively low-cost methane detection technology for SMC monitoring was field tested at an active MSW landfill. To more effectively monitor fugitive methane emissions at MSW landfills, an automatic, low-cost, field-deployable technique is needed to actively monitor methane concentrations. Three test areas within a landfill were selected; SMC surveys were performed both manually and by land-robot using the Landtec TDL-500, a tunable diode laser methane detector. The preliminary field observations indicate that a robotic platform can significantly improve quality in data acquisition for surface methane concentrations at MSW landfills; this paper also discusses the limitations of land-based robots for site-wide methane emission monitoring.

INTRODUCTION

Methane (CH_4) is a key greenhouse gas (GHG) because of its prevalence, its shorter atmospheric life of 12 years, and its high global warming potential that is 28-36 times that of carbon dioxide (CO_2) on a 100-year time scale (Bogner and Matthews 2003). In the U.S., methane accounted for 10% of anthropogenic GHG emissions in 2013. Municipal solid waste (MSW) landfills accounted for 18% of these emissions, making them a key target for methane emission reduction (EPA 2010).

In the U.S., the Environmental Protection Agency (EPA) requires operators of MSW landfills (hereafter referred to as landfills) to perform surface methane concentration (SMC) monitoring to ensure that the cover and landfill gas collection systems are operating properly. Operating landfills must take corrective action if instantaneous fugitive emissions are above 500 parts per million (ppm). Currently, landfill operators or owners generally must perform SMC monitoring on a quarterly basis for landfills along the site's perimeter and along a 'lawn mower' pattern that traverses the landfill at 30 m intervals. Additionally, emissions must be monitored at all cover penetrations and where visual observations indicate elevated methane concentrations (such as distressed vegetation, cracks, or seeps). If methane concentrations at a closed landfill drop below 500 ppm for four consecutive quarters, SMC monitoring is reduced to once per year (EPA 1999, EPA 2015).

In 2015, the EPA proposed changes to SMC monitoring, referred to as enhanced surface monitoring. The new requirements, currently required in California, reduces the interval from 30 m (98') to 7.62 m (25') to account for the high spatial variability of fugitive methane emissions across landfills (CEPA 2014, EPA 2015). This interval is determined by the South Coast Air Quality Management District Rule 1150.1 which divides the landfill into 4,645 m^2 grids (50,000 ft^2) and requires a uniformly spaced route of approximately 241 m (2,600') in length monitored within each grid, equaling approximately 7.62 m (25') intervals as discussed previously (Huitric and Kong 2006). The new standards also require reporting an Integrated Surface Methane (ISM) concentration of below 25 ppm across each grid (EPA 2015).

According to EPA estimates, enhanced surface monitoring is expected to cost, on average, approximately 500 additional man-hours per year, per landfill, compared to conventional monitoring. Under current regulations, an average landfill's quarterly survey requires 42 man-hours; the tighter transverse pattern would require over 165 man-hours for the quarterly survey. Correspondingly, the cost of labor and of rental equipment would increase for SMC monitoring, leading to an estimated increase of \$11,000 per year, per average landfill, to \$76,400 (EPA 2015).

Research has shown that fugitive methane emissions are challenging to measure due to high spatial and temporal variability (Spokas et al. 2003; Rachor et al. 2013). At a landfill, surface emissions are characterized by hotspots, as methane will follow the path of least resistance through cover penetrations, cracks, and seeps (Rachor et al. 2013). Indeed, one study found that 35.4% of the total area of a landfill cell accounted for 99% of the cell's emissions (Spokas et al. 2003). Fugitive methane emissions are affected by local climate factors including barometric pressure, air temperature, soil moisture and temperature and by local condition factors including waste composition, cover soil type and thickness (Goldsmith et al. 2012; Huitric and Kong 2006).

Moreover, fugitive methane emissions vary significantly across geographic regions. Humid subtropical climates are shown to have the highest emissions for all cover types, while semi-arid climates show significantly lower emissions. For intermediate cover, humid subtropical climates emitted an average of 102 g CH_4/m^2/day, while semi-arid climates emitted an average of 3.7 g CH_4/m^2/day (Goldsmith et al. 2012).

To address fugitive methane emissions, several methods and technologies have been developed for SMC monitoring. Initially, landfills utilized a flux chamber and gas chromatography analysis technique to estimate flux over a small surface area (typically 0.125 m^2) per unit time (Eklund 2012). To better address spatial variability, walkover surveys collected air samples along a predefined route and measured these samples in a flame ionization detector (FID) to determine the integrated surface methane concentration over the route, at a resolution of parts per million (Samir and Hossain 2014; Huitric and Kong 2006). Following, portable FIDs were developed to streamline this method; however, the devices require a hydrogen gas supply.

Advances in laser spectroscopy have led to devices that measure with higher resolution and are easier to use in the field. Goldsmith et al. (2012) provides a large-scale application of radial plume mapping and tunable diode lasers (TDL) to measure methane flux at 20 landfills in the U.S. Another sensor, the Cavity Ring Down Spectrometer (CRDS), measures methane to the parts per billion, as demonstrated on leaking natural gas pipelines in Washington, D.C. (Jackson et al. 2014). Recently, robotic platforms with TDL, metal oxide, and electrochemical sensors have been used to develop algorithms for bio-inspired gas detection and methane gas distribution mapping (Hernandez-Bennetts et al. 2012, 2013). Additionally, laser-based trace gas sensors have been mounted on unmanned aerial vehicles (UAVs) for experimental high spatial mapping of methane concentration (Khan et al. 2012).

This paper focuses on the use of a TDL methane detector and a field-deployable land-robot for thorough and cost-effective SMC monitoring at MSW landfills. Preliminary field observations from this study indicate that a robotic platform can improve quality in data acquisition for SMC monitoring at MSW landfills. This paper will present findings from field surveys at an operating MSW landfill with a commercially available TDL device (Landtec TDL-500). SMC monitoring was conducted manually (i.e. a human walk-over survey) and with a land-based robot developed at the Autonomy, Perception, Robotics, Interfaces, and Learning (APRIL) Laboratory of the University of Michigan.

MATERIALS AND METHODS

Survey Method

The preliminary field study evaluated three areas at an operating MSW landfill in the Midwest with active gas collection and some bioreactor cells. The study was performed over three days in a two-week span in early July. The weather was similar on each of these days, with temperature ranging from 67° to 73° Fahrenheit and wind speeds ranging from 6.4 to 12.8 km/hr (4 to 8 mph), and no precipitation.

The three selected test areas are summarized in Table 1. Test Area 1 was in an active area of the landfill operated as a bioreactor with active gas collection. Test Area 2 was in a closed area of the landfill with active gas collection, and Test Area 3 was on sloping grade, on top of an interim waste slope where waste was disposed.

The area surveyed for Test Area 1 and Test Area 2 was 30.5 m by 18.2 m (100' by 60'), for a total area of 557.4 m^2 (6,000 ft^2). Due to space restrictions, Test Area 3 was 18.2 m by 12.2 m (60' by 40'), for a total of area of 223 m^2 (2,400 ft^2).

TABLE 1. Description of Test Areas

Test Area	Area	Cover Status	Description
1	557 m^2	Intermediate	Active area of landfill operated as bioreactor with active gas collection; dry soil, cracks prevalent.
2	557 m^2	Final	Closed area of landfill with active gas collection; soil partially vegetated.
3	223 m^2	Intermediate	Interim waste slope placed approximately one week prior to field testing. Steeper than 4:1 (h:v) slope, cracks/seeps prevalent.

All test areas were surveyed with a traverse pattern of 3 m (10'), in a 'lawn mower' pattern depicted in idealized survey in Figure 1. Additionally, surveys followed EPA protocol for taking measurements at 5-10 cm above the landfill surface and conducting readings at wind speeds below 16 km/hr (10 mph). As the focus was on comparison of results from robotic versus manual surveying, this preliminary field study was substantially scaled down and denser than the EPA's guidance of 4,645 m^2 grids (50,000 ft^2) and 30 m (98') traverse pattern.

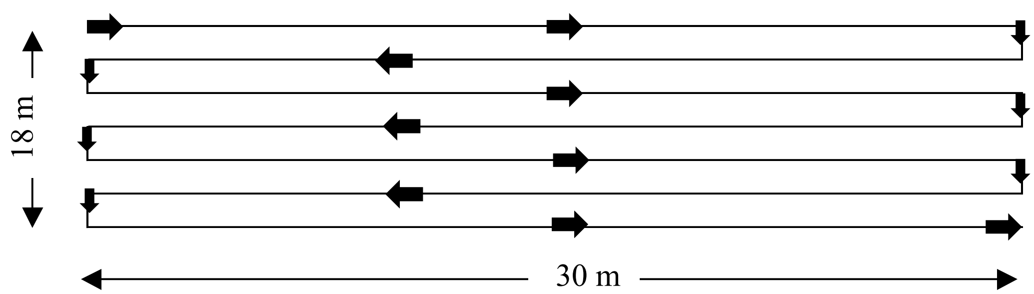


FIG. 1. 'Lawn Mower' Pattern for Test Areas

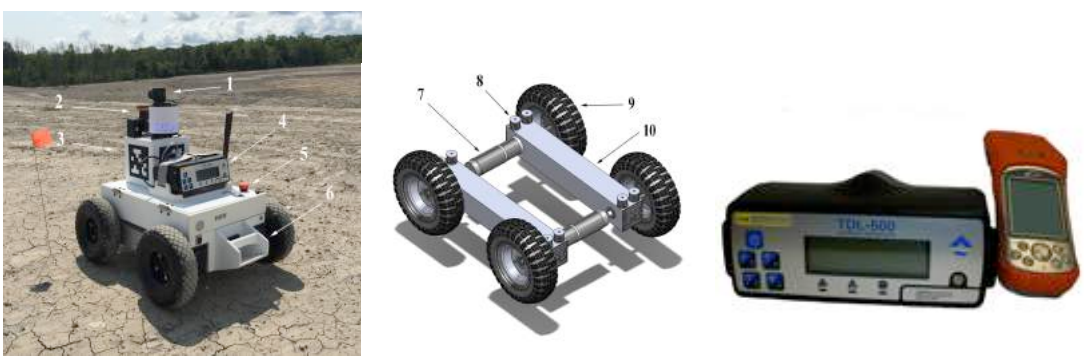
The EPA allows steep slopes and difficult-to-access areas to be excluded from SMC monitoring (EPA 2015). While the robot offered several advantages for the quality and ease of data acquisition, the current platform was not able to traverse the steep slope of Test Area 3. The current robotic platform can navigate slopes of 25% (4:1) or less, but interim slopes exceeded 4:1. Currently, the EPA does not require SMC monitoring on steep slopes or difficult-to-access areas so this issue is not considered critical (EPA 2015). This paper will focus on comparison of the manual and robotic surveys at Test Areas 1 and 2.

Ground-based Robot and Tunable Diode Laser

For autonomous robotic sampling, the APRIL Lab's MAGIC 2 Robots were utilized for field surveys. The MAGIC 2 Robots have been developed for several applications including multi-robot reconnaissance (Olson et al. 2012). Each robot is 66 cm tall with a footprint of 72 cm by 54 cm, and reaches a top speed 2 m/s. The sensor payload includes: an u-blox ANN-MS active GPS, a Hokuyo UTM-30lx laser scanner, a Point Grey Chameleon camera, and an OM2P/OM5P pair of mesh radio relays. These sensors connect to a consumer grade laptop carried within the robot, enabling manual, semi-autonomous, and fully autonomous modes, monitored from a remote operator station. For this experiment, the robot was outfitted with the Landtec TDL-500, interfacing with the laptop, and continuously logged GPS-based georeferenced methane concentrations. Mounting the TDL device on the robot allowed a constant speed and probe distance from the ground during surveying. Challenges of the robot specific to landfills include +/- 25 degrees of ground slope, traversing large aperture cracks, and differentiating grass from solid obstacles.

The Landtec TDL-500, shown in Figure 2, has an accuracy of 0-1000 ppm +/- 2.5%. The device's measurements are more accurate at lower methane concentrations, e.g. at 100 ppm the accuracy is +/- 2.5 ppm, at 40 ppm it is +/- 1.0 ppm, and at 20 ppm it is +/- 0.5 ppm. The device is equipped with an Archer Field PC, a data logger with sub-meter differential GPS and with a telescopic sampling probe with a suction cup, hydrophobic filter, and dust filter. The telescopic probe is held 5-10 cm above the ground for surveying.

TDL devices consist of a light source, a measurement cell, and a light detector. TDL devices are tuned to a certain gas species' wavelength range (on the range of 10 nm). The absorption of light at the light detector is proportional to the concentration of the gas species of interest, in this case methane, at a wavelength of 1650 nm.



(a) (b) (c)

FIG. 2. MAGIC 2 Robot with TDL device used for field testing
(a) MAGIC 2 Robot: 1. Point Grey color camera; 2. Hokuyo LIDAR unit; 3. APRIL tag; 4. TDL-500; 5. Emergency stop button; and 6. 3-in-1 bumper, tip preventer, and handle. **(b)** 7. Motor; 8. Suspension; 9. Wheels; and 10. Rigid aluminum frame. **(c)** TDL-500 analyzer and Archer Field PC with differential GPS (Source: Landtec TDL-500 Technical Specifications)

RESULTS

The field data is summarized in Table 2. The data from both the manual and robot surveys are shown in Figure 3. Only a manual survey was performed on Test Area 3, due to steep interim waste slopes. Test Area 3 had significantly higher methane concentrations, 15 - 210 ppm, than those recorded at Test Area 1 and 2, 3 - 23 ppm and 2 - 5 ppm, respectively. Recordings over 500 ppm were observed but not during recorded surveys. Test Area 1 with intermediate cover had higher average methane concentration readings than Test Area 2. For the manual and robot surveys respectively, Test Area 1 had an average concentration of 9 and 13 ppm, and Test Area 2 had an average of 3 and 5 ppm. In both areas, the robot's measurements were higher than those of the manual survey, although given the small test area size that may not be generally true.

For this preliminary field survey, the robot was manually controlled. The autonomous operation was limited by the robot's current obstacle avoidance parameters, which detected grass as an obstacle. On the test areas, the robot's avoidance system was identifying grass as an obstacle and prevented it from accomplishing the desired 'lawn mower' pattern depicted in Figure 1.

To better visualize the field data, particularly for the manual survey, the Delaunay triangulation function from MATLAB 2015a (*delaunay*) was used to interpolate between the points and create an intensity surface mesh shown in Figure 4. Delaunay triangulation maximizes the minimum angle of all the angles of the triangles in the triangulation to provide equal representation of each data set, in this case for longitude and latitude with corresponding methane concentration. In Test Area 1, the robot survey provides a clearer indication of areas of high emissions, in this case of a maximum of 31 ppm. Test Area 2, in the closed landfill, had substantially lower and more consistent readings, creating a monotonic surface mesh of approximately 3 and 5 ppm for manual and robot survey respectively.

TABLE 2. Summary of SMC Field Survey Data

	Readings	**Freq. of Reading**	**Integrated Surface Methane**	**Std.dev.**	**Min.**	**Max.**	**Delaunay Triangles**
	(No.)	**(s)**	**(ppm)**	**(ppm)**	**(ppm)**	**(ppm)**	**(No.)**
Area 1							
Manual	51	5.00	8.7	4.4	2.7	23.0	89
Robot	5954	0.06	12.8	6.7	5.3	31.3	5192
Area 2							
Manual	51	5.00	2.8	0.7	1.6	4.4	93
Robot	5501	0.06	5.4	0.2	4.9	6.0	5811
Area 3							
Manual	34	5.00	78.1	44.7	15.2	209.8	N/A

DISCUSSION

The robot survey had a higher density of readings, and greater consistency for data acquisition compared to the manual survey. As summarized in Table 2, the robot survey collected more than 5000 readings per test area, while the manual survey collected 51 readings per test area, i.e. 100 times fewer data. The manual survey provided a discrete data set with collection limited by the Archer Field PC, which had a maximum of 1 reading every 5 seconds. The robot, equipped with a consumer-grade laptop, was able to collected data practically continuously with approximately 17 readings per second, or 1 reading every 0.06 seconds. The increased frequency of readings provide a clear identification of hot spots and of the general concentration profile across a test area.

Additionally, the surveys differed in terms of the telescopic probe distance above the ground and the travel speed of the device. The telescopic probe, per device recommendations and EPA guidelines, is to be held consistently at 5-10 cm above the ground while walking at a speed of 3 to 5 km/hr (2 to 3 mph). The use of a robotic platform has the ability to ensure a standardized and consistent approach to the measurements, whereas manual measurements may deviate from these recommendations, affecting the quality of the measurements. Compared to the manual survey, mounting the TDL device on the robot provided greater consistency during surveying by providing constant speed and constant distance from the ground surface

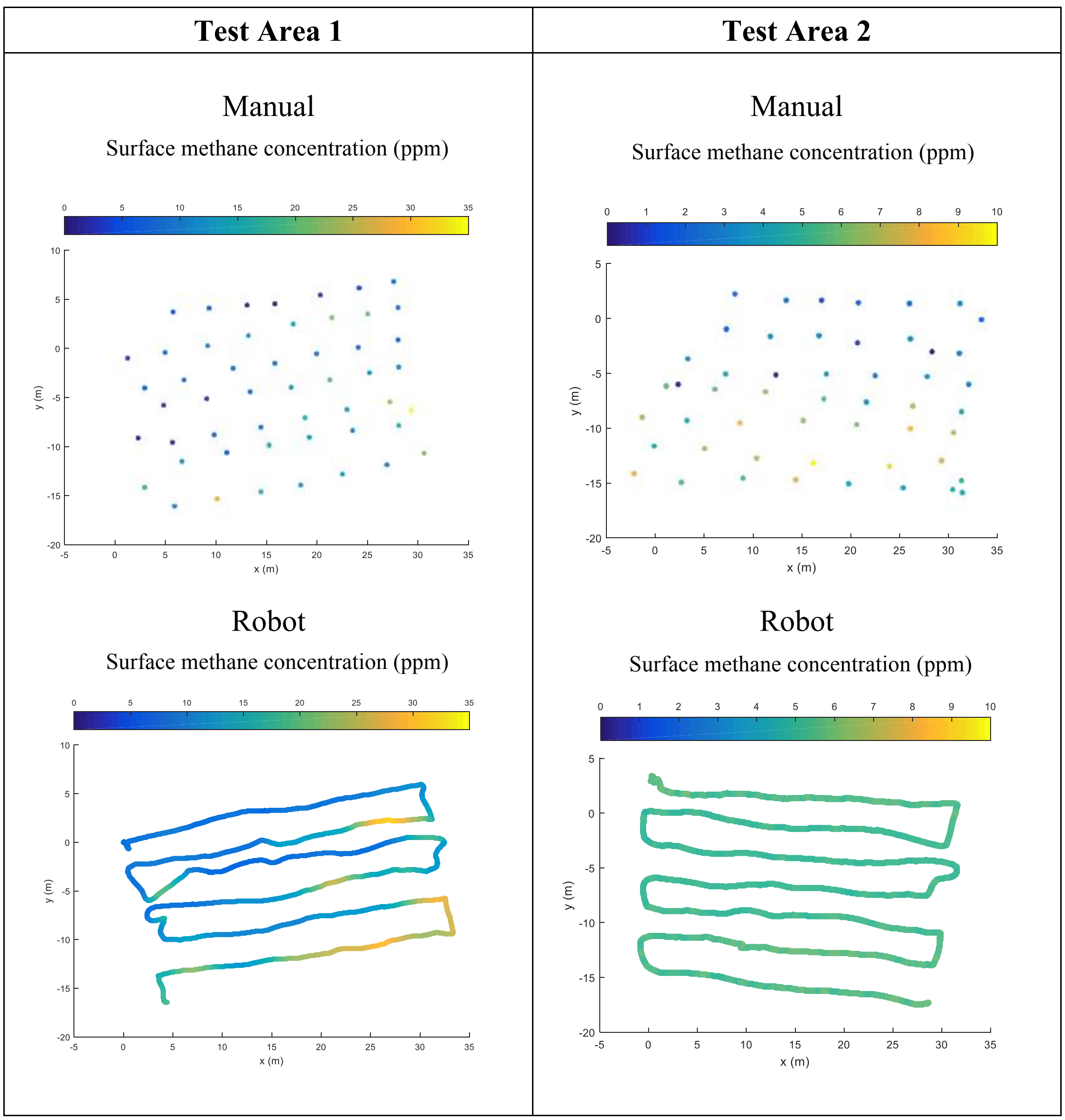


FIG. 3. SMC Measurements for Manual versus Robot Surveys

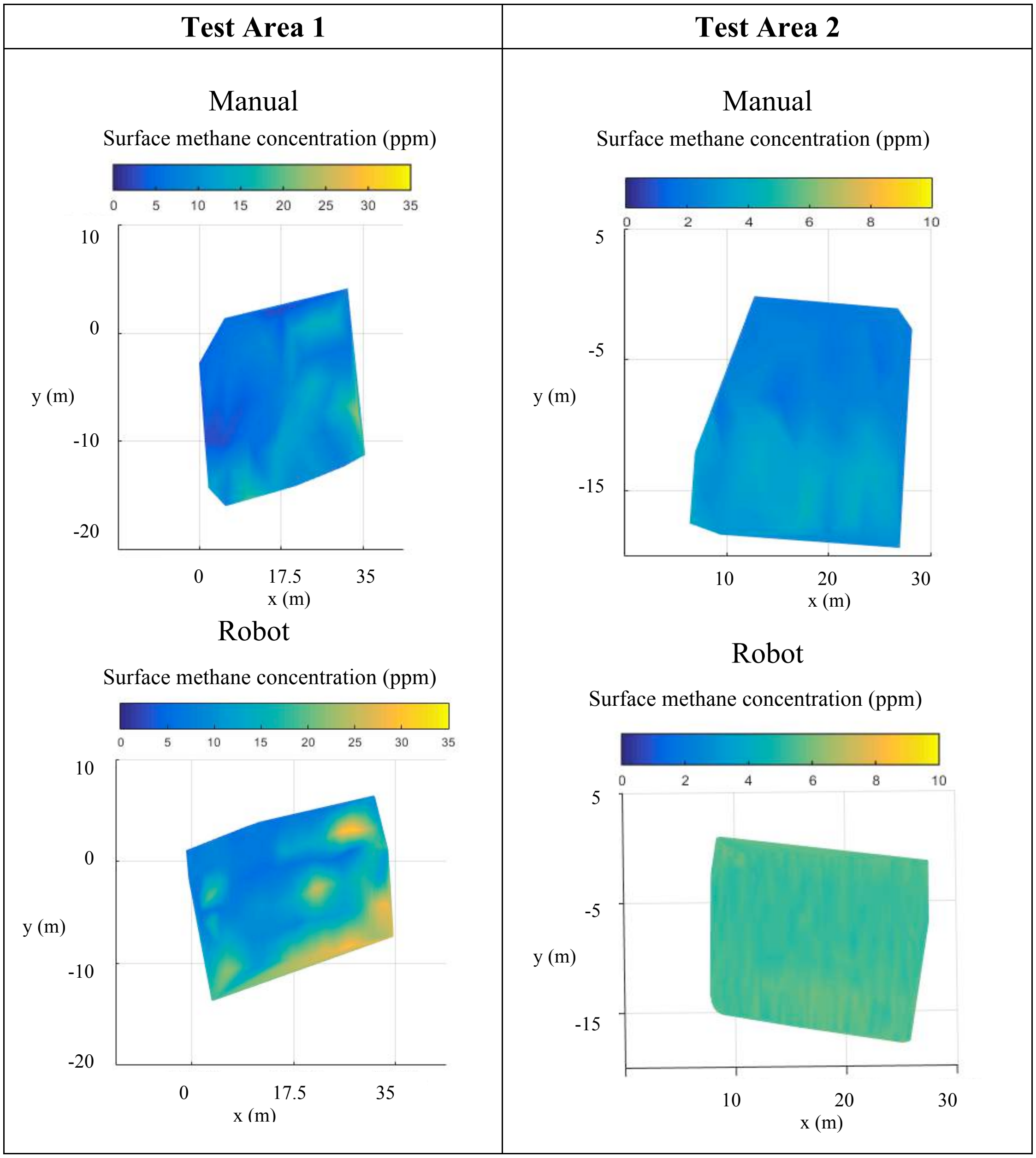


FIG. 4. SMC Delaunay Triangulated Maps for Manual versus Robot Surveys

CONCLUSIONS

The robot-enabled SMC monitoring provided higher quality data acquisition over conventional walking survey by standardizing the probe height and travel speed, and by increasing the frequency of readings over a grid.

Preliminary field observations demonstrate that SMC monitoring with higher frequency of readings resulted in higher integrated surface methane (i.e. mean methane concentration over a given area), as demonstrated for Test Area 1 and 2. Additionally, higher frequency of readings more readily indicates SMC hot spots in an area with varying concentration readings such as Test Area 1. The robot-based SMC survey provided nearly continuous readings at 17 readings per second, compared to conventional survey with one reading every five seconds.

For active areas within the landfill, the dense traverse pattern of 3 m (10') intervals indicates that SMC varies significantly and that wider traverse patterns may not capture local steep variations in SMC readings that would affect integrated surface methane calculations. As the current interval spacing required at a federal level is 30 m (98') there is the possibility that integrated surface methane is not representative of the area. Conversely, closed areas of the landfill indicate relatively uniform SMC and a wider traverse pattern may be appropriate for these areas.

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