Digital Twin Enabled Methane Emission Abatement Using Networked Mobile Sensing and Mobile Actuation

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2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI) | 978-1-6654-3337-2/21/$31.00 ©2021 IEEE | DOI: 10.1109/DTPI52967.2021.9540133

***Abstract*—Digital Twin is a revolutionary concept from Industry 4.0 for solving physical experiments that cannot frequently repeat due to high cost and safety concerns. It is well known that increasing methane emissions have caused potential global warming, which doesn't satisfy carbon neutralized statement. We proposed a Digital Twin enabled methane emission abatement framework using drones to update real-time data to measure methane emissions to address these issues. We validated our Digital Twin by separated subsystems of targeting in methane emissions mapping and prediction. The preliminary results demonstrate that Digital Twin is an efficient tool in abating methane emissions and contributes efforts to global climate change.**

***Index Terms*—Digital Twin, Mobile Sensing, Mobile Actuation, Methane Emission Abatement**

I. Introduction

Global Methane Challenge [1] as an international campaign of reducing methane has attracted much attention for responding to potential global warming. Methane is the second most significant known source of greenhouse gases, accounting for most affection that contributes to global warming. It is well understood that if the global climate warms enough, glaciers will melt, releasing unknown ancient viruses/bacteria [2], which will have an impact on human health. Methane is abundant in the natural world, derived from bacteria in the soil, water, and ruminant animals. Besides, human activities such as fossil fuel burning, dairy farms, landfills, oil wells, and other sources of methane are primarily found in industry and agriculture. As a result, the main objective of methane abatement is to reduce methane emissions into the atmosphere, especially from human activities. However, there are still many impediments to abating methane emissions. The primary research challenges, in particular, are a lack of an appropriate method for measuring time-varying methane concentrations (in a spatial sense) and determining how to monitor methane emissions during unknown disturbances. These two primary research objectives are critical for abating methane emissions.

Prior research into methane detection has resulted in numerous advances in sensing and actuation methods, including remote sensing by satellite [3], aircraft, or sensors on the tower to demonstrate methane spreading. However, these remote sensing techniques are constrained by space weather [4]. Due to bad weather, methane concentrations may be jammed or shifted, making monitoring more complicated and efforts hard in abating methane emissions. Another common technique is regional surveillance, which entails putting several sensors on the ground to collect methane data simultaneously. However, the installation, repair, and calibration criteria for these approaches [5] will substantially increase their expense and complexity.

To address these shortcomings, we introduced a Digital Twin (DT) framework for reducing methane emissions with swarming Unmanned Aircraft Vehicles (UAVs). The DT is a virtual representation of the physical instance that provides real-time data services. Real-time data from the UAV we used in our proposed framework would be extremely beneficial for simulating real-time methane distribution. This approach can be advantageous for mapping and forecasting methane emissions because it needs fewer field trials but has a high-level prediction precision. To do so, we utilize UAV toolbox [6], ROS[1], Gazebo[2] and Web App [7] to deploy our DT platform, and we use the UAVs as mobile sensors and actuators to track methane diffusion and will be able to spray methane neutralizers (e.g., biochar [8]) to abate methane emissions. The following are the challenges of using UAVs as mobile sensors and deploying DT: 1) Connectivity instability and security concerns about real-time data transfer from UAV to DT platform, 2) The uncertainty associated with methane distribution concentrations that are time-varying, adding ambiguity to the Digital Twin. To tackle these challenges, we designed our DT system to: 1) transmit data opportunistically while UAVs are not performing tasks (e.g., path planning, hovering, etc.), 2) apply the physical principle to develop a core model of methane emissions, and 3) utilize machine learning algorithms to iterate DT using real-time data efficiently. In summary, the contributions of this work are as follows:

- We present a DT that contains UAV toolbox, ROS, and Gazebo for methane emission abatement;

1. https://www.ros.org/
2. http://gazebosim.org/

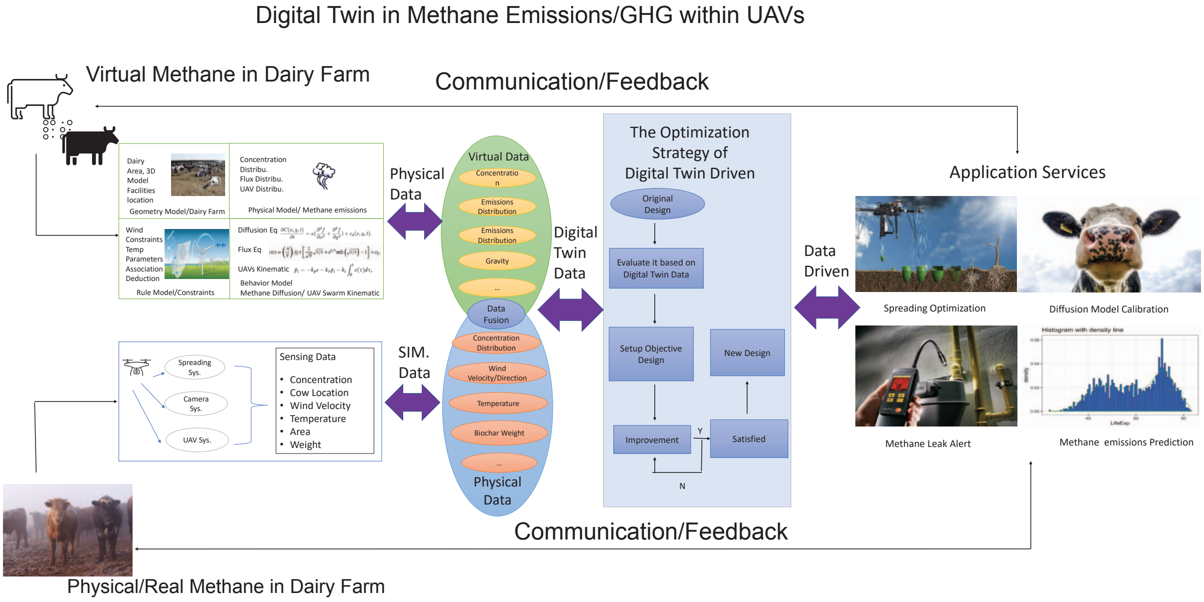

Fig. 1. Digital Twin in Methane Emissions Quantification Analysis

- We tested our DT prototype of methane emissions to demonstrate the feasibility, challenges, and opportunities of our DT.

II. Digital Twin in Methane Abatement

Due to the ineffectiveness and inaccuracy of the conventional approach of monitoring methane emissions (please refer to section I), we need to develop a method that accurately represents methane emissions processes and is also cost-effective. As a result, DT as an Industry 4.0 proposition has come to our attention, and to our best knowledge, there is no relevant work using DT to abate methane emissions. DT utilizes various subsystems, including sensors and actuators, to gather data from the natural environment. DT will analyze these data in order to make a decision and give actuators instructions. Figure 1 illustrates the role of each subsystem of DT in methane emissions. Although DT has been shown to be effective and valuable, there are numerous unresolved questions, which would be addressed in the following sections.

A. The Physical Principle Behind Methane Emissions

In this section, let us assume wind speed is at zero, then the methane as gas satisfies fluid dynamics, which is dynamically spreading in the time domain and space domain, respectively. Partial differential equation (PDE) (1) is used to describe methane emission dynamics:

$$\frac{\partial C(x,y,t)}{\partial t} = \kappa(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2}) + c_d(x,y,t), \tag{1}$$

where $C(x,y,t)$ is methane concentration, x and y are directions in space, t is the mission time, κ is the diffusivity constant and c_d is methane source.

We can easily construct virtual methane emission prototypes using the equation above and assume that the actual wind speed is zero. The following step is to consider the impact of the uncertainty disturbances.

B. Uncertainty Conditions of Methane Emissions

In general, the uncertainty conditions include but not limited to wind, local temperature, different types of methane emission sources (such as point source, uniform distribution area source, non-uniform distribution area source, etc.), and the other unknown issues. Different uncertainty conditions need to add specific terms on equation (1) to approach accurate methane emissions.

Here is the idea of how to apply wind field into the PDE. Once we get the current wind speed and direction, we use the fluid dynamics equation as wind force split into x and y-direction, respectively. This term needs to be added to methane disturbance and actuators' side. Hence, based on different wind speeds and their directions, it would approach natural methane emission better. Local temperature changes increase or slow down the movement of methane molecules, affecting methane emissions significantly. Especially, temperature changes could be affected by facilities, such as dairy farms, landfills, oil wells, etc. By adding temperature terms into DT in order to monitor methane emissions and methane leaking.

Overall, the key components, which are realizable, real-time data interacting, behavior matching, modular structure, trackable, and re-programmable [9] of DT have been discussed, and those uncertainty conditions are the way to approach actual environmental methane emissions. As for the other unexpected or unknown disturbances, we may use an algorithm to trained real-time data to feed our DT (e.g., machine learning).

III. Networked Mobile Sensing and Actuation

Mobile sensors have advantages in acquiring fine-grained information and extensive detection spatial range for dynamic

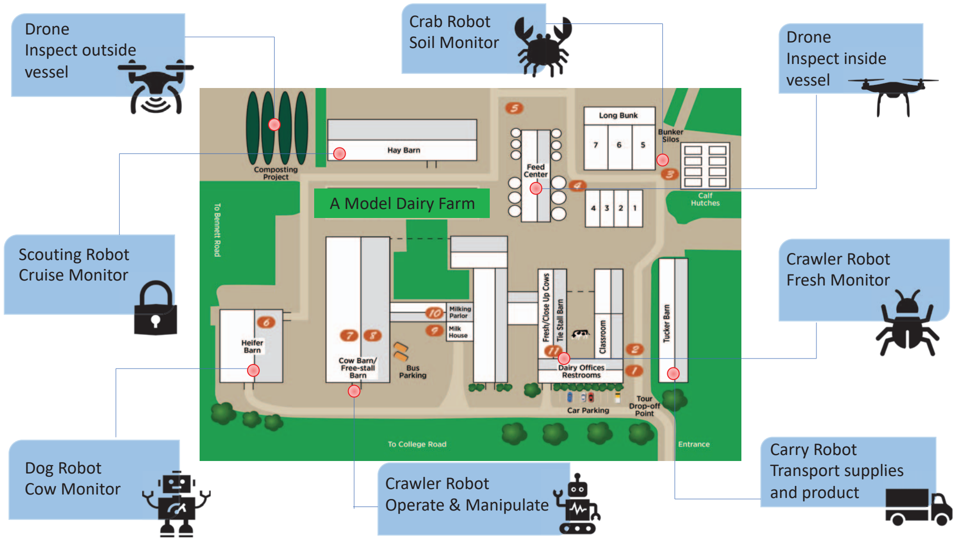

Fig. 2. Mobile Robots Perform Various Tasks in a Dairy Farm

system characterization. Our UAVs fly back and forth to map desired land fields, dairy farms, etc. Based on the DT philosophy, not only one robot but also many robots within different mission tasks are equipped with sensors to do sensing fusion that provides data to DT. Figure 2 demonstrates the possibility that we can have multiple mobile sensors to finish sensing tasks. From this figure, the more accurate information we want to feet DT, the more different types of mission sensors should be equipped.

Besides, the UAVs can also be used as mobile actuators to help DT find the best location to spread Biochar for abating methane emissions as fast as the UAVs can. Furthermore, to make UAVs fly to the desired locations as fast as possible, we need to explore an optimal coverage control problem to find a better actuators distribution strategy to effectively sampling methane data and exchanged the information between DT and physical entities. The related coverage control methods include lead follower [10], potential field [11], virtual structure [12], Centroidal Voronoi Tessellations (CVT) [13], etc.

After we combined mobile sensors and closed-loop control actuators, we have a robust wireless sensor and actuator network (WSAN) for information exchange. Then, the power management decides whether to stay or act based on remaining energy needs to be further noticed.

IV. Preliminary Results

To validate our DT, we 1) conduct UAV toolbox, Gazebo, and ROS experiments for UAV flight path and waypoints following, and 2) we write a script of applying PDE (1) as the platform of DT to build methane emissions dynamic processes.

We utilized the ROS toolbox in Matlab to make the connection between the UAV toolbox and Gazebo. The coverage area flight paths of UAVs were tested. Gazebo drove the physical engine to demonstrate flight status and how UAV flights under uncertain conditions. Figure 3 shows examples of UAV fixed-point flight under different altitudes. The swarming UAVs

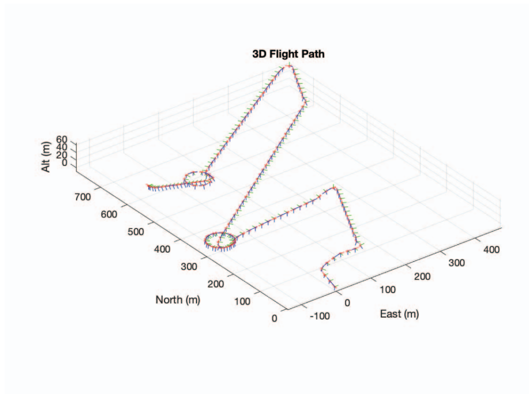

Fig. 3. UAV Waypoint Flight Path within UAV Toolbox

were implemented in Gazebo at Figure 4 to check swarming UAVs of coverage control feasibility. Figure 5 demonstrates the prototype of methane emissions under no wind effects, and we observed a methane diffusion process that approaches the maximum diffusion concentration (in the spatial domain) almost at the middle of simulation time (total simulation time is 4s), which demonstrating the methane diffusion characteristics.

Since there is no standard evaluation metric of DT, then we only check task completion on each subsystem. The 3D flight path of testing fixed-point flight that performs well; It is challenging to test coverage swarming such as the CVT algorithm in Gazebo, but we observed the swarming tasks perform efficiently. The last validation of methane was successful in simulating the methane diffusion process. The only thing we need to notice about the order of PDE is true that it affects diffusion time and area.

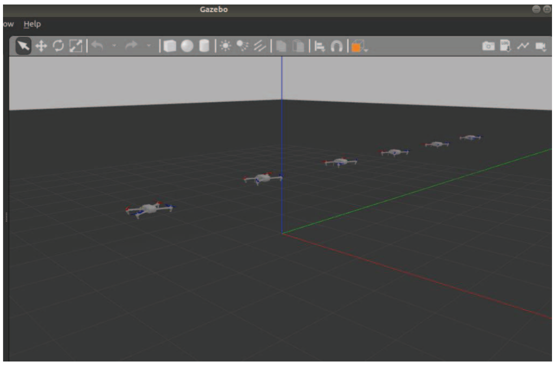

Fig. 4. Swarming UAVs in Gazebo

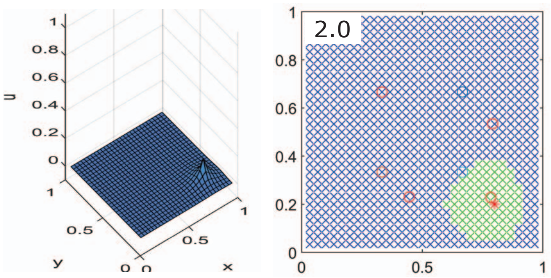

Fig. 5. Methane Diffusion Process

V. Discussion and Future Works

Networked sensors and actuators are mainly composed of UAVs, and their battery is being limited to the total mission lifetime. Besides, the payload of UAVs also needs to be considered that we need to use UAVs to spread Biochar to abate methane emissions. Thus, selecting a coverage strategy to cover the entire field as fast as the UAVs can is the critical component of implementing keep real-time data updating.

When we simulate the methane diffusion process, the order of PDE does matter of methane emissions in time and spatial domain, respectively. There are supper diffusion and subdiffusion that are corresponding to different orders. What's more, adjusting the order of PDE to meet those unexpected issues (wind field has many types, turbulence, eddy, meandering [14], etc.) as referred to fractional order is the way to approach DT at the practical situation of methane emissions. Once the DT of methane emissions is settled, we can easily predict and abate methane by controlling our UAVs.

The opportunities and challenges of DT introduced by a combination of UAVs as mobile sensors and actuators, the real-world data input, etc., as virtual representation can be further explored. We plan to explore the DT in the following directions further: 1) optimizing the UAVs sampling operation schedule to increase the opportunity to capture methane emissions and minimize the total mapping and prediction cost, 2) deploying Web App as user interaction to combine these subsystems (methane emissions, UAVs, sensing, actuators, etc.) into DT, and 3) collecting actual methane emission data to enhance the DT by selectively hovering at desired locations that allow high-fidelity data acquisition and transmission.

VI. Conclusion

In this paper, we presented a DT enabled methane emission abatement framework that utilizes UAV toolbox, ROS, and Gazebo with mobile sensors and actuators - UAVs. The core physical principle of DT is presented, and we illustrate that the impact of methane emissions can be reduced via mobile sensing and Biochar spreading. In the end, we demonstrated some preliminary results on our UAV's flight path, swarming actuators, and methane diffusion processes. The preliminary results of DT in methane emissions indicate that DT has a great potential to handle methane abatement more effectively and efficiently.

Acknowledgment

We gratefully acknowledge the support of CA SGC grant entitled "Mobile Biochar Production for Methane Emission Reduction and Soil Amendment".

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