Air-flow sensing for vehicle length estimation in autonomous driving applications

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***Abstract*— Flow sensing has been investigated in the context of underwater and aerial robotics in the past decade. It has not been explored for applications in autonomous ground robotics. In this work-in-progress paper, we investigate the use of air-flow sensing for the applications in autonomous driving. More precisely, we investigate the use of air-flow sensing for vehicle length estimation by conducting computational-fluid-dynamics (CFD) simulations.**

Keywords — Perception, flow sensing, autonomous driving, computational fluid dynamics

I. INTRODUCTION

In recent years autonomous driving [1, 2, 3] has gotten increased attention from researchers in academia and industry, alike, all around the world. Perception sensors commonly, and extensively, used in autonomous driving research include vision, lidar, radar and sonar. All of these sensing modalities have their own strengths and limitations, but none of them can be used to estimate the length of a leading vehicle like trucks.

Air-flow sensing as a perception modality has been used in underwater [4, 5, 6] and aerial robotics [7, 8, 9]. Flow sensors are low cost, and the flow signal processing usually has a low computation cost. Flow sensing has been used for the purposes of localization and fluid speed estimation in underwater and aerial robotics.

In this work-in-progress paper, we investigate the potential uses of air-flow sensing in autonomous driving. The main goal of the on-going work is to predict the size of the truck in front of a car. We employ computational-fluid-dynamics (CFD) simulations for our experimentation. This work has been conducted as the first author's bachelor dissertation [10]. To the best of our knowledge, this is the first work that investigates the use of flow sensing as a perception modality, for applications in autonomous driving.

The rest of the paper is organized as follows. Section II discusses works on flow sensing from sister fields of robotics i.e. underwater and aerial. Section III presents the tools that we employ for our research and section IV presents the preliminary results. The paper concludes in section V.

II. RELATED WORKS ON FLOW SENSING FOR ROBOTICS

As, to the best of our knowledge, no research has been carried out on using flow sensing for perception in ground robotics or autonomous driving, in the following subsections we give an overview of the flow-sensing research done in underwater and aerial robotics.

A. Applications of flow sensors in underwater robotics

The applications of flow sensing in underwater robotics include qualitative localization, map-based localization and fluid speed estimation etc.

In [4], a rainbow-trout shaped robot equipped with 15 pressure sensors is used for map-based localization using flow sensing as the perception modality. The maps used in the study are based on CFD models of a flow channel. The pressure sensors are used for flow sensing, as pressure data can readily be converted into flow estimates.

In [5], a rainbow trout shaped robot equipped with 16 piezo-resistive sensors was used. However, only data from the nose sensor was used. The study presents map-based localization and loop-closure detection in an underwater environment, with flow-sensing as the sole perception modality.

The above mentioned and related research shows that there is a potential for flow sensing to complement the existing underwater localization methods such as sonar and vision. Flow sensing can be especially beneficial in low visibility and murky environments, in comparison to vision sensing in underwater robotics.

B. Applications of flow sensors in aerial robotics

The application of flow sensors in autonomous airships has gained increased interest in the robotics community. The localization of aerial robots has also been investigated with the aid of flow sensing, in both online and offline modes [7]. For localization, algorithms similar to those mentioned earlier in the context of underwater localization have been used.

The problem of estimating wind velocity on a hexacopter using data from onboard sensors has been investigated in [8]. For estimating the wind speed aerodynamics of the air vehicle also should be considered. The experiments done in [7], showed that it is possible to reconstruct the vertical velocity if the horizontal velocity is known. This is very important for our own work as well, as in the case of autonomous driving, vehicle velocities can easily be estimated using sensing modalities of vision, lidar and radar etc.

However, not every study in the literature relies on air-flow sensing for wind estimating [11]. In [11], the air velocity predicting method using only inertial measurement unit (IMU) and GPS-velocity for quadrotor is presented. The main idea is to look at the GPS data changes by using the tilt and power of the rotors. For example, in the case of the opposite wind, the quadrotor will fly the shorter vector than in non-windy weather. The results showed that it is possible to estimate the air velocity of the quadrotor in this manner.

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C. Air-flow sensors

A variety of approaches for flow sensing have been investigated in the literature. Below we present a few.

In [12], a flow sensing system inspired by animal hair cells is presented. The device [12] is inspired by the construction of a hair cell, which uses the calibration of hair to measure the flow direction and speed in underwater environments. The device is sensitive to temperature changes, so for the correct measurement constant temperature should be used.

In [9], the Hot-Film sensor is presented. The principle of this sensor is that a thermal element relies on the direction of the heat, as the flow cools it.

Estimation of the wind velocity using optical flow sensors is presented in [13]. The study shows that such sensors can be used to estimate wind speed, as well as estimate the wind direction with an average 0.6 s sample period [13].

In conclusion, many different technologies have been investigated for flow sensing, and thus open the way for more wider future applications of flow sensing as a perception modality in robotics.

III. SIMULATION TOOLS

The following subsections give an overview of the technologies and methodology used for our work.

A. Computer Fluid Dynamics

CFD, is a technology that uses numerical analysis to analyse the fluid flows. Due to a lack of existing research on air-sensing applications in autonomous driving, we have conducted our preliminary investigation in simulations.

There are many different toolboxes for CFD simulations. For this work, the OpenFOAM [14] toolbox is be used.

B. SimScale

SimScale is a cloud service which allows to conduct CFD, Finite Element Method (FEA), and thermal simulations in one online platform [15]. CFD simulations, which are used for this work, are done using OpenFOAM open-source toolbox.

The main reason for selecting SimScale for this work is its straightforward and accessible visual interface, allowing even not experienced users to easily create a simulation. In addition to that, there are a wide variety of tutorials available [16]. However, as SimScale is not an open-source but a commercial product, it has its own pricing [17]. Fortunately, SimScale has a Community license, which allows using only 3000 computation hours for one account, however, this is more than enough for this project.

C. Creating a scene

The scene, i.e. the simulation experimental setup for this work, is an environment with the two vehicles (a truck and a car) moving after each other, simulating the real-life situation of the cars moving on the highway. The main aim of that was to experiment with the different speeds, lengths of the truck, and distances to the car. For the simulations, free vehicle models from the GrabCAD website [18] are used[1].

For the experiment we use a single truck model, changing the size of the trailer. The main reason behind using the single truck model is that the aerodynamics of the cabins are different for each truck and may cause noise in the results. However, the problem of noise due to the different cabins of the trucks have to be considered in practical applications.

Before starting working on the project test simulations were done to estimate the computational time for the simulations in the way that the SimScale community plan will satisfy our needs. As the results, one simulation at average took 100 computational hours to complete. Based on this information it was decided to select only two speed levels and two truck sizes to experiment with.

For the scene, two different sizes of the truck were selected, 10 m which is common for cargo trucks, and 17 m, as the maximum length of the truck in Europe. Distances between cars were calculated based on the Estonian Traffic Act. It is stated that the time to cover the distance between cars should be two seconds in the built-up area and three seconds outside the built-up area [19].

Creating the scene is done using 3D editor Blender [20]. The main reason for using Blender for this work is that Blender allows us to convert models into standard triangulated language (STL) file format, which SimScale allows to use for simulations.

Unfortunately, SimScale does not allow to get data from the single points on the model, therefore the result should have been manually downloaded and used in another program. For analyzing the results ParaView [21] was selected, which is mainly used for analyzing the CFD data.

As SimScale uses OpenFOAM toolbox, almost every data generated is saved and is available for analysis. For the analysis it was decided to select 5 points on the surface of the car in the longest scene and look at how it changes over time. These points were selected based on comparison pressure maps from simulation for 60 km/h for two different truck lengths.

The possible sensor locations are shown in figure 1. For the simulations, only one side of the car was simulated to decrease the computational time of the simulations, using the symmetry function, meaning that the simulation results are same for the both sides of the car. Therefore, the sensors are located on one side of the car.

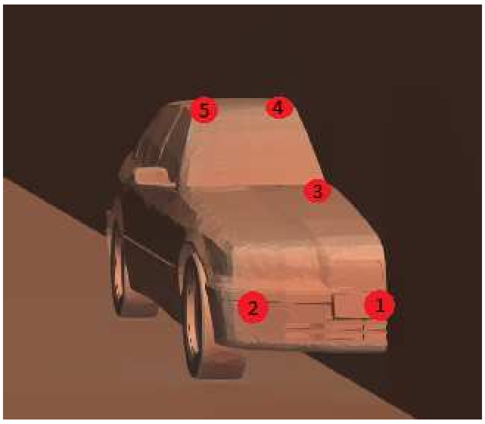

Fig. 1. Proposed locations for air-flow sensors

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[1] We acknowledge the creators/contributors of the models, Andrea Carlappi (for the car) and Oraltosun (for the truck).

IV. SIMULATION RESULTS

The following subsections show the results achieved by the simulations.

A. Results

In total, were conducted 10 simulations, testing two speed levels and two sizes of trucks. For the saving interval, 1000 s were selected. For the analysis data from 5 points on the car are used (as shown in figure 1).

For each simulation, data from each point was collected using the ParaView probe tool and to be analyzed later on. Results of the simulations are presented in tables 1 and 2. From the results, it is clear that data from all sensors differ based on size and distance between vehicles.

The data from the pressure sensors is done in incompressible flow simulation meaning that the values are relative. The reason for selecting the relative data over absolute values is that we are working with the pressure differences, which are more visible and understandable in lower values, compared to the absolute values.

Environment	**Sensor locations**				
	1) Car number plate	***2) Right side of the front***	***3)Hood, close to window***	***4) Roof centre***	***5) Roof right***
60 km/h 10 m truck	99,83	62,93	19,59	-59,42	-49,13
60 km/h 17 m truck	88,68	45,69	4,82	-96,12	-77,14
90 km/h 10 m truck	221,4	121,83	12,98	-176,0	-145,29
90 km/h 17 m truck	272,86	145,58	20,72	-196,1	-157,58

Table 1. Simulation results for safe distances (Pa)

Environment	**Sensor locations**				
	1) Car number plate	***2) Right side of the front***	***3)Hood, close to window***	***4) Roof centre***	***5) Roof right***
60 km/h 10 m truck (2x safe distance)	85,46	46,92	-0,8	-78,4	-66,04
60 km/h 17 m truck (2x safe distance)	114,69	59,62	10,27	-90,7	-72,32
90 km/h 10 m truck (1/2x safe distance)	206,86	135,31	44,43	-123,7	-99,86
90 km/h 17 m truck (1/2x safe distance)	95,15	63,61	-9,09	-57,31	-57,41

Table 2. Simulation results of different distances between truck and vehicle (Pa)

In addition to the initial simulation, two additional simulations were also conducted. First is for a 14 m truck to compare the results with the initial simulation to find the relationship between data and the correlation in the results. Second is for the windy environment with 5 m/s wind coming from the side. The results are presented in table 3.

Environment	**Sensor locations**				
	1) Car number plate	***2) Right side of the front***	***3)Hood, close to window***	***4) Roof centre***	***5) Roof right***
60 km/h 10 m truck	99,83	62,93	19,59	-59,42	-49,13
60 km/h 14 m truck	127,4	63,67	11,86	-72,58	-69,71
60 km/h 10 m truck wind 5 m/s	147,84	108,41	29,77	-73,32	-51,8

Table 3. Additional simulation results (Pa)

B. Analyzing the results

From the results presented in tables 1, 2 and 3, it is clear that data from the same environments and different truck lengths do differ in the same direction as the length of the truck changes. However, the Pressure value for 60 km/h does decrease with the increase in length of the truck (*cf.* table 1), while at 90 km/h it's the opposite.

The results show that there is a change in the pressure sensor readings with change in speed, even if the actual relationship between the two is not established by such limited experiments.

However, the next question is whether it is possible to predict the size of the truck in front of the vehicle. For answer to that question, it was decided to conduct an additional simulation with the new size of the truck and look at how the data change.

It was decided to create a new model of truck with a length of 14 meters. The hypothesis is that it is possible to find a relationship between length and pressure data.

For testing the proposed hypothesis, the addition simulation for 60 km/h scene was conducted. The results of the simulation are shown in table 3. The results shown in table 3, showed correlation in data between initial simulations (table 1) at sensor locations 1, 2, 4, 5.

The changes in the distances between truck and autonomous vehicle showed very promising results. As we may see from the table 2, with the changes in the distances we have also changes in the pressure data. For example, as we get closer to the truck the pressure values decrease while getting further away from truck giving the bigger pressure values. Knowing the distance to the truck we could possibly distinguish truck sizes more accurately.

It is also seen from table 2 that for the 2x safe distance, the 60 km/h 10 m truck model showed us almost the same results in sensor locations 1, 2, 3 with the 60 km/h 10 m long truck in the initial simulation at table 1. This could mean that there could possibly be a relationship between the length of the truck and air-flow data. Unfortunately, due to lack of simulation data, this relationship was not discovered in this work but may be further researched for the real-world environment.

However, the real-world experiments could possibly show different results. The reason for that is the simulations conducted for this project used the model, where wind is coming only from the front side. Meaning that wind flows only from the front, creating turbulence in the scene while not accounting for the wind coming from the sides, as it is for real-world applications.

V. CONCLUSION

A. *Conclusions*

In conclusion, the research showed some promising results. Most of the proposed locations of the sensors showed the distinguishable values in terms of truck length and distance from the car. The relationship between the length of truck and air-flow data, unfortunately has not been found, however it might be possible to create a look-up table which could be used for estimating the truck length.

Conducting the additional simulation, with a 14 m long truck, showed the correlation between the simulation data. The changes in the truck lengths showed promising results, correlating with the data from 3 out of 5 sensors.

B. *Future directions*

For the future research, there are some problems which could be further researched, which are outlined as follows.

Firstly, the effect of wind on the results need to be further investigated. Secondly, the distances between vehicles other than safe distances could be further researched as well. In practice, such scenarios do occur in real-life traffic. The experimentation on real platforms is also a future avenue to investigate.

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