Deep Tunnel Sewerage System monitoring using a swarm of autonomous dualcopters

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I. INTRODUCTION

This project aims to achieve a swarm surveillance system to be implemented in the Deep Water Sewerage system in Singapore. This project involves the design of a custom flight platform capable of operating in the environmental conditions in the sewerage system and to allow this flight platform to reliably fly autonomously for prolonged periods of time. It also involves the making of a flight platform that can operate synchronously with the drone swarm to cover the entire monitoring area in an efficient and effective manner

There are three main components to this project. The first component in the system is the flight platform. We need to design a durable and effective flight platform with a decent flight time and performance to operate in the harsh and constrained environment of the sewerage system.

The second aspect for the project is the drone swarm infrastructure. This talks about the communications systems in place which allows the robot to operate in a swarm fashion. It also talks about how the system is deployed and used by the users and customers.

The third aspect is the monitoring systems. This involves the camera stream and autonomous navigation of the robot within the sewerage system without causing collisions.

These 3 aspects come together to form the ideal deep sewerage monitoring system which allows for robots to replace humans operating in the harsh conditions of the Deep Tunnel Sewerage system.

II. THE FLIGHT PLATFORM

A. *Analysing the requirements for this flight platform*

There are several considerations that need to be made to allow the flight platform to be effective in the Deep Tunnel Sewerage system.

The first consideration is the size. The Deep Tunnel Sewerage system is a constrained space which means that there is not much space for the drones to fly around in. To minimize the chance of collisions, the drone needs to be as small and compact as possible to allow for the drone to operate efficiently and quickly. Being small also allows the drone to get into tight spaces and monitor more cramp areas.

The second consideration is the durability and versatility. The drones will be operating in harsh conditions with possible water leakages and other environmental factors. This means that the drone needs to be as durable as possible and it also has to be somewhat waterproof.

The last consideration is cost. Since a swarm system is going to be deployed, each drone needs to be as cost effective as possible to allow for the swarm to be practical in terms of cost. This makes cost one of the most important considerations for this swarm platform.

B. *Custom Flight Platform*

Given the considerations that have to be made, quadcopters and conventional drones simply don't fit the bill. This is because, firstly a conventional quadcopter needs to be quite big to carry the required payload for fully autonomous operation. Furthermore, quadcopters are not very cost efficient as each drone can take upwards of 500 dollars to make and that makes the whole idea impractical in terms of cost.

Being inspired off of the design of the Spherical Flying Vehicle[1], we designed a dual-copter system which uses a custom frame design to achieve maximum efficiency in terms of the flight platform. We call it the **SentiBot.**

C. *Flight drive system*

The novel frame design on our SentiBot platform is one of the reasons for its ideal characteristics for swarm activity. Our frame design goes against the conventional design of 4 motors by replacing it with a custom counter rotating EDF **(E**lectronic **D**ucted **F**an**)**. This reduces the number of high-speed moving parts on the design and therefore lowers the complexity and chance of failure. By using an EDF instead of a propeller design, we also managed to get much better static thrust performance which is ideal of hovering in these types on drones.

The counter rotating blades also negate the counter-torque effects that would have been present in a single motor design such as the Spherical Flying Vehicle [1]

Figure 1-SentiBot view*

Figure 2- SentiBot Top View*

D. *Control system*

For control, we went for 4 control surfaces much like a conventional coax-copter. These control surfaces work much rather in the same way as airplane flaps and direct air to achieve control. By enclosing the whole design in a cylindrical shaped frame, we enable the frame to contain all the essential electronics inside the frame and prevent damage to the moving components.

E. *Flight efficiency measurements*

By employing, high speed motors with bullnose propellers, we are able to achieve the maximum efficiency for a similar sized drone. At a max thrust of 800g running a 4s (16.8V) Lithium Polymer battery, the SentiBot is the smallest ever created drone of its kind. Other drones that employ the coaxial motors and the control surfaces, are many orders of magnitude bigger due to the inability to achieve this much thrust per space occupied.

F. *Modularity*

Using the cylindrical design as a reference point for the design, we added modularity by ensuring a complete bolt based design. The SentiBot can be easily accessed with just a hex driver. You can also easily get access to the main processing board by just removing the top cover.

MOTOR TECHNICAL DATA:

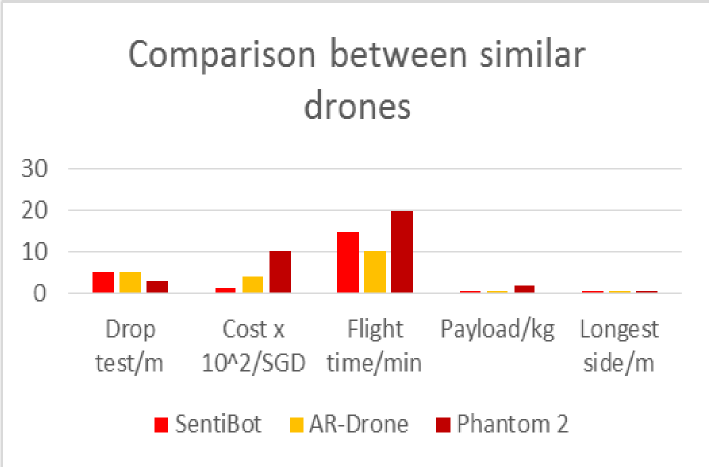
	NO LOAD		ON LOAD				LOAD TYPE
VOLTAGE	CURRENT	SPEED	CURRENT	Pull	Power	EEP	Battery/prop
V	A	rpm	A	g	W	%	
11.1			1.8	80	20.0	4.0	LiPo×3/T3030
			4.3	160	47.7	3.4	
			7.7	247	85.5	2.9	
14.8	0.9	5927	1.9	100	28.1	3.6	LiPo×4/T3030
			4.7	200	69.6	2.9	
			10.7	370	158.4	2.3	

Figure 5- Motor thrust test**

G. *Enhancing large scale manufacturing*

Lastly, the frame design allows for easy large-scale manufacturing. The 3D files which make up the components in the frame are simple 3D shapes that can be easily molded and cast thus making it easy to manufacture. As of now the frame uses a Polylactic acid (PLA) material, but this material could be changed to more durable ones like polycarbonate or Nylon-6.

In conclusion, the frame design allows for a durable and modular swarm platform which is able to be easily implemented into swarm systems.



III. Electronics Design

A. *Main Processor*

The electronics design is a critical part of the platform as the electronics provide the foundation for the control system of the robot. Since the robot is going to have to do computing intense tasks like vision processing, it is paramount that we have a processor on board. Our processor of choice was the Intel Edison. It provides a decent amount of computing power operating at 500MHz with 512MB of RAM. It also has 4GB of onboard storage for any applications or programs. Since it runs a flavour of Debian Linux, Ubilinux, it is extremely easy to use and program.

B. *ATMEGA 328 and lower level processing*

We realized that we needed a separate microcontroller to manage the control logic to avoid too much computing pressure on the Edison. We ended up using the ATMEGA 328 microcontroller chip and flashing the control logic onto it. By using an ATMEGA 328, we also obtained additional sensor expandability options through getting more GPIO which could be used. To combine the main processor with the lower level processor to get a dual CPU system, we designed a custom PCB which makes a very versatile control board for this system to be extremely dynamic.

Figure 3- PCB fabricated*

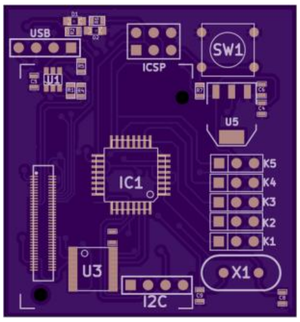


Figure 4- PCB render*

C. IMU(Inertial Measurement Unit)

The control loop also required an Inertial Measurement Unit (IMU) to detect orientation and compensate for oscillations present in the frame. By using an I2C interface to the ATMEGA 328, we managed to connect the MPU6050 and a barometer to the chip which allows for the chip to compensate for oscillations. This will also help to stabilize the frame as seen in the following section. The MPU6050 is connected to the custom PCB through a set of header pins which allows the IMU to either be temporarily or permanently connected to the PCB.

D. Navigation camera

The drone is also equipped with a camera capable of viewing in IR wavelengths. Since the deep tunnel sewerage system will require the drone to operate in low light conditions, this IR camera solution will allow the drone to see even in pitch black conditions. This is because there can be IR emitters onboard the drone which illuminate the surrounding in IR. In addition, LED flashlights can also be added to allow for navigation based on visible light as well.

E. High definition camera

Since the system needs to monitor pipes, a high definition camera is placed on the bot as well, for the crew to analyze the footage and determine if there is anything wrong with the piping in the sewer system. The two cameras are used in tandem simultaneously by the onboard processor but only the high definition camera stream is streamed down to the operator.

F. Collision avoidance systems

As a fallback to the navigation camera, the drone is also equipped with ultrasound distance sensors to prevent mid-air collisions between bots and to prevent colliding with walls and pipe. This is tapped into by the software to allow for the drones to have a fallback navigation system purely on ultrasound if necessary.

G. Flight Drive system specifications

The power electronics consists of 4 1C 1200mAh batteries, 2 30A super light ESCs and 2 4000kV 1306 motors. The motor have a max current draw of 8A each and taking into consideration that the max thrust of each motor is 370g the gram per current rating for each motor is 46g/A. Since the weight of the SentiBot is about 320g, the nominal current draw during a hover would be about 7A. That gives us a flight time of about 10-15min. This is a pretty respectable amount of flight time for a conventional drone. This configuration can of course be changed in case the user requires more power or more flight time.

H. Power Supply management

Lastly, I would like to talk about the power management system in the SentiBot. We will be using the in-built BEC in the ESC which provides clean 5V out to power the board. The board also has an onboard 3V regulator to provide power to the Edison and the logic level converter which allows UART communication between the 1.8V Edison and the ATMEGA328 for the Edison to send high level commands to the ATMEGA 328 controller. The SentiBot can also be equipped with wireless charging to allow easier and convenient charging.

IV. DRONE SWARM INFRASTRUCTRURE

A. Why use a swarm?

The deep tunnel sewerage system is a large complicated network of sewers and this makes using a single drone to monitor all of that extremely hard. Furthermore, given a certain area in the Deep Tunnel Sewerage system, multiple SentiBots will be able to cover it faster and more efficiently than a single one. This is why we employed a swarm system in our monitoring design.

B. Implementation of drone swarm

The drone swarm is going to be implemented on 2 separate levels. On the first level a group of 10 SentiBots are considered one swarm. A single human operator is able to manage and operate all 10 SentiBots as they are fully autonomous. The operator simply needs to be present to ensure nothing goes wrong and for emergency stops of the system if something does go wrong.

The video feed from each robot is transmitted to the operator as they fly around and this video feed is transmitted from the operator to the main command station where engineers look at the footage and determine whether the pipes need repairing. This is good as only the SentiBots needs to enter the sewer system and the operator can stay outside. This prevents the operator from being exposed to the harsh conditions in the sewer system.

The next level of implementation is that there could be multiple operators surveying separate areas of the sewer system at the same time. This is where GPS systems come in and the data from each operator is tagged with a GPS location so that the crew at the main command station know which part of the sewer system they are looking at. Given these 2 levels of implementation, separate communications infrastructure is needed to allow the swarms to operate coherently and for the information to reach the main command station in a presentable and easy to use manner.

C. Inter SentiBot communication

The swarm system of 10 SentiBots first need to be able to communicate with one another. This is done through the Intel Edison board. Since the swarm of 10 bots will stay in relatively close proximity to one another and the operator throughout the operation simple 2.4 GHz frequency band can be used for communication.

A peer to peer communication network can be set up where each SentiBot and the operator's control device acts as a node. Video signals are bounced through nodes until it reaches the final operator. The operator's device can then send the video signal to the main command station.

D. Swarm to command station communciation

As mentioned above, the video stream from the swarm needs to be sent to the main command station where engineers can analyze the piping and determine the condition of the piping. This can only be done through communication between the swarm and the main command station.

When the operator receives the video signals from the SentiBots, the device that he is using to receive the signals will first tag the video stream with the swarm's GPS location before uploading it to the cloud through the 4G network where the main command station is able to access the video feed from. The 4G and GPS is accessible because unlike the SentiBots who are in the sewer system, the operator can be above ground and have access to services like GPS and 4G networks. Video feed can also be archived in the cloud for later use.

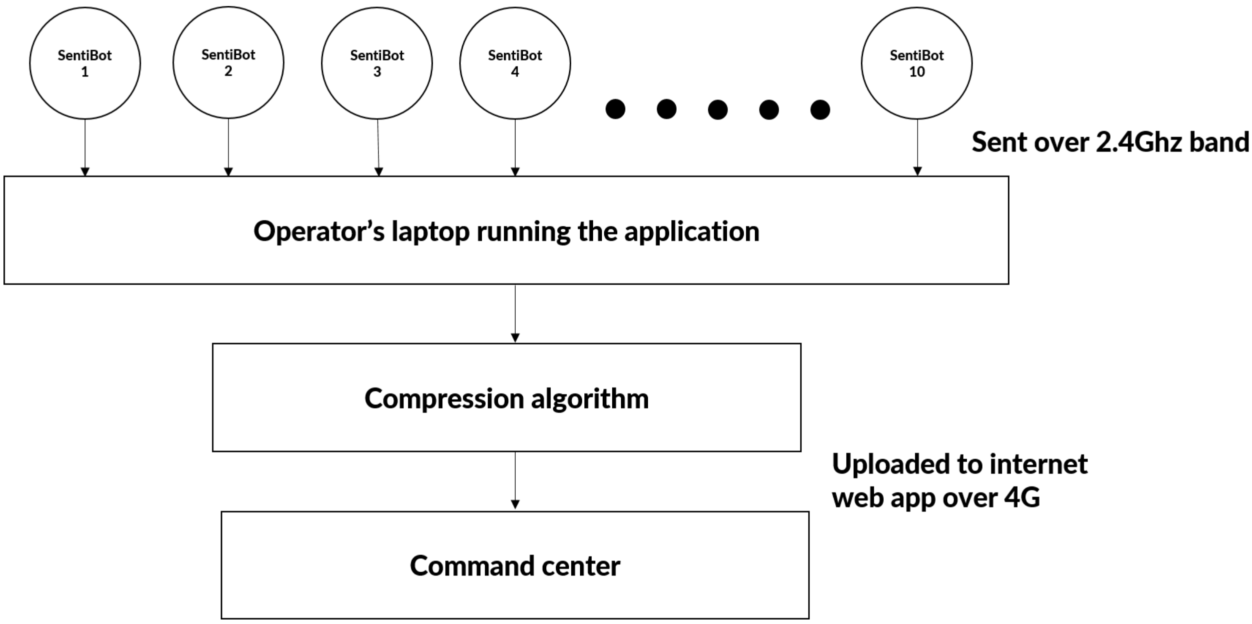
E. Operator Usage

The operator needs to be able to access the video feed from the SentiBot and be able to force land the SentiBots if anything goes wrong. This is done though an application on his computer. His computer has a 2.4Ghz transceiver plugged in for long range communication and can communicate with the SentiBot swarm for video feed data and also send the kill command which causes them to force land.

Through the operator's computer, the video feed can be seen by the operator and he can make sure no mid-air collisions occur.

F. Command Centre Usage

The command center accesses the video feed through a web application designed by us. It allows the monitoring engineers to monitor the pipes remotely and from the comfort of their offices. The design of the UI is detailed in the following software architecture section.



V. SOFTWARE ARCHITECTURE

A. *Introduction to Software Architecture*

This section will talk about the software systems that make all the systems works. I will be starting off with the systems that make the SentiBot fully autonomous before moving on to the systems that are required for the swarm infrastructure to work as intended.

B. *PID loop*

The control algorithm used in the SentiBot is similar to all the other control algorithms used in typical quadcopters. Implementing the classic PID control loop, we allow the sensor data to be mapped into error values that can be used to compensate for frame errors and instabilities in the frame. This basically allows for the drone to remain stable despite environmental factors.

The control algorithm first reads the I2C bus and outputs the data from the IMU which has been preprocessed by the Digital Signal Processor (DSP) on board the IMU. This allows for the control algorithm to get filtered and processed yaw-pitch-roll (**ypr**) data for use in the PID algorithm.

The processed **ypr** values are sent through the respective PID loops for their specific axis and used to obtain 3 error values for each of the x, y and z axis. These error values can then be used to output to the servos, which then tries to bring the system back to the stable state by moving the specific servos.

The barometer also enables altitude hold using another PID loop. All of the control algorithm runs onboard the ATMEGA 328.

C. *Vision algorithms*

The main sensor on board the SentiBot are the cameras. There are 2 of them on board with one of them being used for navigation. The navigation camera is interfaced through using ROS (Robot operating system) as the processor on the SentiBot is running Ubilinux which is a flavor of Debian Linux. Since Debian supports ROS, we can tap onto the pre-existing resources in ROS to do autonomous monocular SLAM. This allows us to do navigation.

The autonomous monocular SLAM which runs on the bot allows us to also get a low resolution map of the surroundings which also helps the engineers visualize the surroundings that they are monitoring.

The pre-built resources in ROS also offers us the ability to overlay the high definition camera footage over the low resolution map which can further help the engineers determine if the pipes needs maintenance or repair.

D. *Swarm algorithms*

Using the global 3D map that is shared and generated by the swarm of SentiBots, they can calculate optimal positions for themselves and position themselves in places where they will be useful. This causes them to fan out and cover a larger areas than what a single bot will cover.

This also helps the bots prevent midair collisions as each of them know where they are specifically in space relative to the other bots.

E. *Collision avoidance system*

Fallback systems are critical to ensure no investment is lost when system failure occurs. This is done using 4 collision detection IR sensors on the SentiBot which prevents unintentional collisions with walls and pipes. This is done on the ATMEGA 328 chip which reads the outputs of the IR distance sensors and ensures a sufficient distance is maintained between the SentiBot and any solid objects.

This is done on an interrupt based system in the ATMEGA 328 where the sensors are read at time sensitive intervals whenever the interrupts activate.

F. *Video streaming interface*

Since the primary operational purpose of this system is to act as a monitoring tool, the ability to easily access the live video stream is important. As an added bonus, this implementation of the video streaming interface allows the footage can be viewed remotely over the internet. The video stream is compressed on board the operator’s device before being uploaded to a web app via 4G.

G. *Operator & monitoring crew UI*

The operator and monitoring staff will need to view the footage over a user friendly AI to minimize the learning curve while learning to use the system.

The design of the web application is both aesthetically pleasing and also functionally succinct. There are 2 important functions that this system needs to perform. This first one is the video feed which is displayed in separate video feeds with one for each individual SentiBot. Each video feed is also tagged with the GPS location. The second function is organization. The video feed is organized based on GPS location making it easy for the engineers to find their way around the video feeds. The cloud based storage allows the engineers to view the footage at their own pace without any rush.

The application on the operator’s computer is also designed with an elegant user interface which makes it easy to use. It also helps to present information in an intuitive manner which minimizes human error.

VI. DEPLOYMENT AND REAL-LIFE IMPLEMENTATION

A. Operational Procedure

This section outlines the real life implementation methodology and what the end users can expect the workflow to be like. PUB may first wish to obtain a single swarm unit with the 5 SentiBots to test out the system.

First, the operator is given a certain GPS location to survey the sewer system in. He brings the 10 SentiBot system to the location before deploying them into the sewer system through access ports built for the bots to get in.

The bots enter the sewer system and using monocular SLAM, start mapping out the immediate surroundings. As they obtain a rough 3D map from the monocular SLAM algorithm, the swarm algorithms kick in and they start fanning out into more optimal positions.

The operator makes sure that no mid-air collisions occur though the live video feed being streamed to his computer from each of the 10 SentiBots. He also uses the 4G network to upload the video to the cloud web app with the GPS tag. The video feed is stored for engineers to inspect the sewer system.

After 10 minutes, the SentiBots would have covered a total area of 1km diameter in every direction in the sewer system. An alert will go off to the operator that the battery is running low and the SentiBots will home and land back at the operator.

The operator can now return to charge the SentiBots and then proceed to another location to survey. This can be done by multiple operators simultaneously to speed up the process.

B. Benefits of our system in real life implementation

There are 3 main advantages to our system in real life. Cost, durability and reliability. The cost of our system is superiors to other system based on conventional quadrotors as each SentiBot only costs approximately 100 dollars to make compared a minimum of 200 dollars for a quadrotor.

In terms to durability, the SentiBot's electronics are completely enclosed and its propellers are fully shielded. This makes it more durable and rugged than drone alternatives. That minimizes the chance of loss of investment when crashes occur.

Our system is also highly reliable as it relies on cloud services rather than local video feed storage and that minimizes loss of information. Regular back-ups also helps ensure no video feeds are lost. Our system also requires very little infrastructure to be placed into the construction of the sewer system. This makes it very plug and play and easy to use compared to the other alternatives.

C. Cost considerations

This section will detail how the SentiBots system is extremely cost effective as compared to other implementations based on conventional drones. As a quick comparison of cost, each SentiBot costs approximately 150-200 SGD depending on the payload. In contrast, a DJI Phantom costs upwards of 1000SGD for a single drone. A swarm of 10 SentiBots tops off at 2000 SGD which is equivalent to just 2 DJI Phantoms. Due to the small size, reduced material cost, and reduced complexity, we are able to achieve an extremely low cost which makes the SentiBot system very cost effective in a swarm system.

VII. CONCLUSION AND FINAL WORDS

In conclusion, the SentiBot swarm system provides an extremely cost effective implementation of swarm drones into the Deep Tunnel Sewerage system to eliminate the need for humans to expose themselves to the harsh environments within the tunnel.

It may even offer savings to the government and PUB as they will not require maintenance men to go down to monitor the piping as the automation of that might be more cost effective in the long run.

SentiBots also provides an extremely rugged robot which can survive harsh conditions in the sewer system. Some future work that could be done on the system is to figure out how to branch off into other parts of the world by attempting to automate more harsh jobs which put excessive strain on humans.

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*Figure 1,2,4,5 are self-generated
** Figure 2 is obtained from motor seller website (https://www.65drones.com/collections/motors/products/dys-bx1306-4000kv)