Autonomous Drone Systems for Large Structure Inspections

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***Abstract*—This paper presents a simple, yet computationally less-intensive method for coverage path planning around large structures. The approach makes use of properties of Lissajous curves for the task at hand. Multiple elementary inspection surfaces and their modifications are proposed that can be for the process of inspection. The effectiveness of our proposed approach is demonstrated through simulations in physics-based environments.**

***Index Terms*—lissajous curves, multi-drone, path planning**

I. INTRODUCTION

Autonomous drones and robots are widely deployed in the inspection of large structures such as bridges, buildings, ships, wind turbines, and aircraft, as it is an arduous task for the inspector to perform [1-2]. The inspection is of critical importance since missing details could affect the performance and integrity of the structure. But as necessary as inspection is, it is also dangerous, time-consuming, and expensive as in most cases, scaffolding is required to inspect these large structures.

The flight time of a UAV might be shorter compared to the time needed to perform a complete structural inspection of large structures; therefore, we need to use multi-drone systems to inspect these structures reliably [3-5]. Inspection missions usually involve coverage path planning, model reconstruction, and the actual inspection of the structure.

Coverage path planning (CPP) is the task of determining a path that passes over all points of an area or volume of interest while avoiding obstacles. Extensive research and development have been done for single drone path planning [6-11] and data integration to reconstruct the models [12-13] for inspection. In this paper, we develop the algorithms and methodologies for a multi-drone system to inspect large structures such as ships or offshore oil installations.

Discrete CPP algorithms divide the planning problem into two steps: viewpoints generation to generate a discrete set of views and optimal path generation using multi-goal planning to connect the views. Continuous CPP is mainly focused on following a trajectory while perceiving sensed information continuously.

Norman Hallermann and Guido Morgenthal [14] have discussed visual inspection methods based on airborne photos and video taken by unmanned aerial vehicles. One of the features included in the setup was a "come home function," which guarantees a safe landing when the connection between the ground station and the flight system is interrupted. A GPS-based matrix system helps in flying at a constant distance to the structure. The Point of Interest (POI) feature allows flying around a structure at a constant distance to the object with a continuous orientation of the flight system and the camera towards the object's center.

The article review in [15] has put together recent work in coverage path planning and model reconstruction. Coverage path planning generates an optimized path that guarantees the complete coverage of the structure of interest to gather highly accurate information for shape/model reconstruction. The drawbacks of the CPP solution is that they require explicit information about the geometry of the structure in the form of blueprints or maps and the optimization task is time consuming.

The majority of existing approaches attempt to reduce the computational cost [16] i.e. time needed to compute and execute the inspection mission, avoid collision with the structure of interest and gather information with sufficient resolution for anomaly detection. A cost effective approach to path planning through the use of Lissajous curves have been proposed in [17 - 19].

The main contributions of the proposed research work can be summarised as:

- Develop a novel 3D coverage path planning methodology using Lissajous curves.
- Implement and validate the method for inspection of large structures through simulations in physics based environments.

The organization of the paper is as follows, Section II defines and explores the properties of Lissajous curves that have been extensively made use of for path planning. Section III describes the controller that has been made use of in the simulations. Section IV looks at the various simulations carried out to implement the proposed strategy. Section V concludes the paper and ways to improve the usage of Lissajous curve-based coverage path planning.

II. LISSAJOUS CURVES

In this section, we look at the definition and properties of Lissajous curves that have been made use of for the problem.

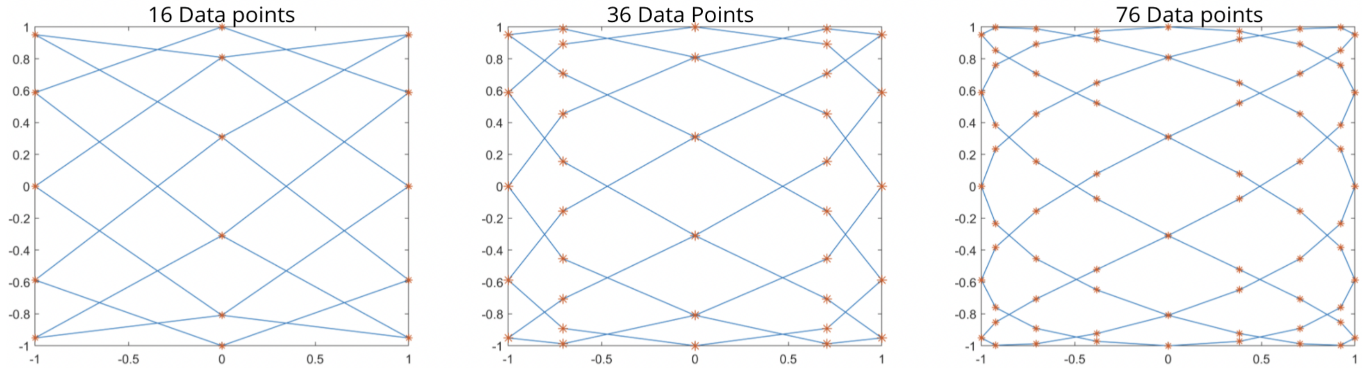

Fig. 1. Lissajous curves with different number of data-points

Lissajous figures are patterns produced by the intersection of two sinusoidal curves, the axes of which are orthogonal to each other. Such curves are chosen so that they cover an entire surface. The parametric equations that produce the curve are:

$$x = A\sin(at) \tag{1}$$

$$y = B\sin(bt + \phi) \tag{2}$$

where A and B represent amplitudes in the x and y directions ϕ is the phase angle. Depending on the values of a and b, we can determine the number of horizontally aligned "lobes" and the number of vertically aligned lobes. Rational ratios produce closed or still figures, while irrational ratios make figures that appear to rotate.

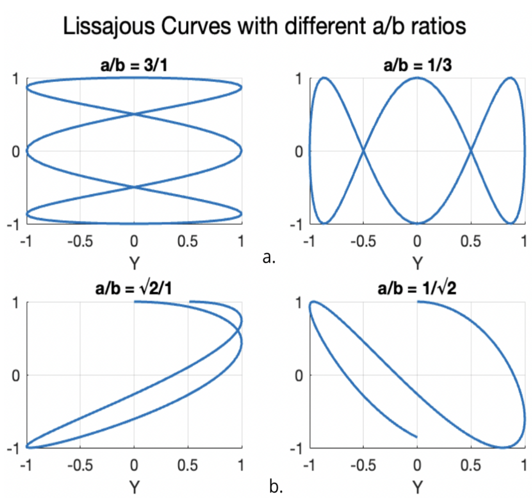

Fig. 2. a: showcases the difference in no. of lobes with a/b ratio. b: showcases curves with irrational a/b ratio.

In our methodology, we propose to enclose the structure under consideration within a surface of revolution such as a cylinder, a cone and variations of the same. We then make the drones trace out Lissajous curves on the surface of revolution.

The approach is conservative, as it may not conform to the shape of the structure and the drone may move closer to certain portions of the structure in comparison to others. However, this approach does not consider the explicit geometry of the structure to inspect, thus, saving on lot of memory and can easily be implemented at inconsequential computation costs.

As Lissajous curves are on a plane, we need to describe transformations between 2D and 3D surfaces to carry out 3D surface inspection.

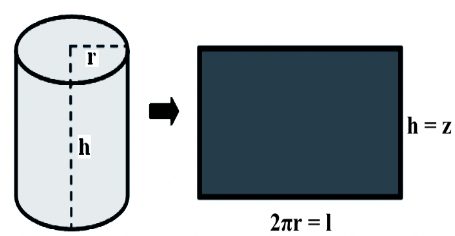

Fig. 3. Lissajous curves transformed to the surface of two separate 3-D cylinders

Theorem 1. The Lissajous curve on the surface of a cylinder is given by

$$x = r\sin\theta \tag{3}$$

$$y = r\cos\theta \tag{4}$$

$$z = B\sin(bt + \phi) \tag{5}$$

wher r and θ are in the cylindrical co-ordinates.

Proof: Let each point of the Lissajous curve is taken as a complex number represented as,

$$L = A\sin(at) + iB\sin(bt + \phi) \tag{6}$$

where real part of L is used to obtain the x and y co-ordinates while the imaginary part of L corresponds to the z co-ordinate and let the l be defined as,

$$l = A + B \tag{7}$$

The r and θ, in the cylindrical co-ordinates, corresponding to this case can be obtained as,

$$r = \frac{l \times n_1}{2\pi} \tag{8}$$

$$\theta = \frac{real(L) \times 2\pi}{l} \tag{9}$$

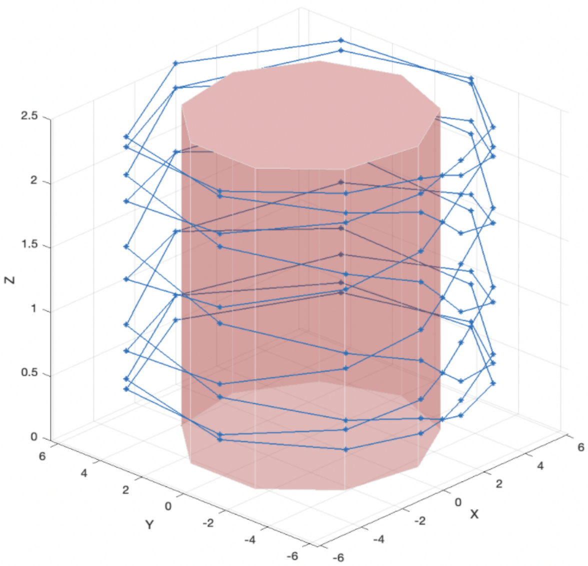

Fig. 4. Lissajous curves transformed to the surface of a single 3-D cylinder of constant radii

and the x and y co-ordinates are obtained as,

$$x = r \sin\theta \tag{10}$$

$$y = r \cos\theta \tag{11}$$

The variable n_1 helps assign the required constant radius for the cylindrical surface covered by the Lissajous curves. The path illustrated can be carried out either completely using one drone or multiple drones.

A. Constant Radius

The most straightforward transformation carried out is the conversion from the Lissajous way-points on the plane to the

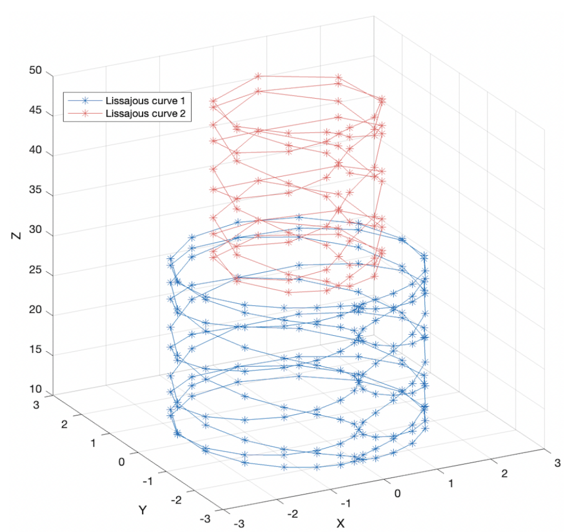

Fig. 5. Lissajous curves transformed to the surface of two separate 3-D cylinders of constant radii

surface of a single-cylinder with constant radii.

Theorem 2. Assuming n_1 as a constant, the radius obtained from the Lissajous curves defined would be constant and hence the corresponding 3-D cylinder is also of constant radius.

Proof: By assigning A and B as unity i.e. $l = 2$ and n_1 as a constant C, we obtain

$$r_c = \frac{l}{2\pi} = constant \tag{12}$$

and the x and y co-ordinates are obtained as,

$$x = r_c \sin\theta = f_1(\theta) \tag{13}$$

$$y = r_c \cos\theta = f_2(\theta) \tag{14}$$

B. Variable Radius

The motivation behind varying the radius of the 3-D inspection surface is to facilitate the inspection of structures such as towering buildings and skyscrapers that reduce floor surface area with height. Also, having a variable radii helps in better conforming of the enclosing surface with the actual shape of the structure. **Theorem 3.** Assuming n_1 is a function of z, i.e.

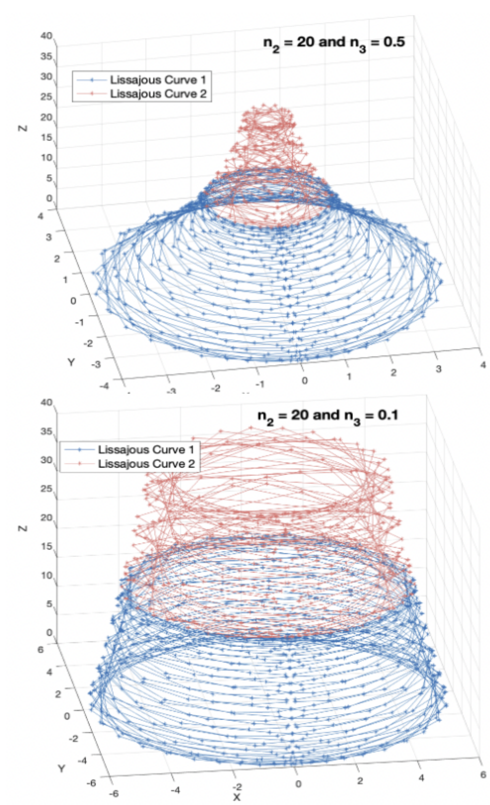

Fig. 6. The variation of n_3 that change the curvature of the inspection surface

height, such that the radius obtained from the Lissajous curves defined would be continuously decreasing, the corresponding 3-D cylindrical surface obtained would also have decreasing radii with increasing height.

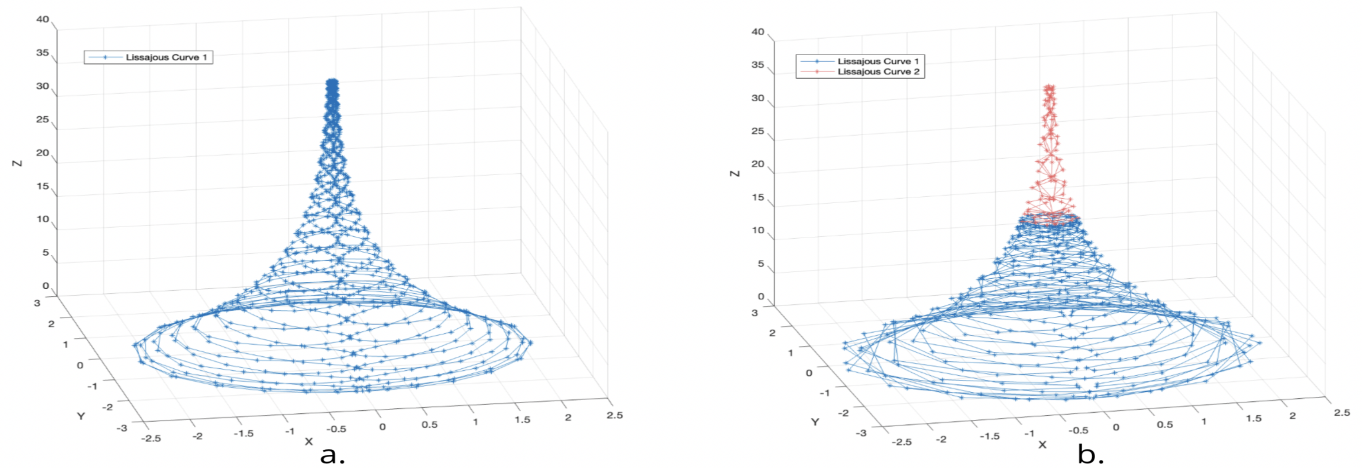

Fig. 7. a. Single Lissajous curve with continuously varying radius. b. Two separate Lissajous curves with a different number of way-point concentrations.

Proof: By assigning A and B as unity i.e. $l = 2$ and n_1 as a function of z, the choice of n is made such that,

$$n_1 = \frac{n_2}{e^{n_3 \times z}} \tag{15}$$

where n_2 and n_3 are constants which decides the base radius and curvature of the inspection surface.

$$r_v = \frac{l \times n_1}{2\pi} = f(z) \tag{16}$$

and the x and y co-ordinates are obtained as,

$$x = r_v \sin\theta = f_1(\theta, z) \tag{17}$$

$$y = r_v \cos\theta = f_2(\theta, z) \tag{18}$$

The way-points on the Lissajous curve become closely spaced with a decrease in radius and therefore, it is necessary to adjust the number of way-points for varying radius to prevent way-point confusion for the drones as well reduce redundant way-points. This is achieved by concatenating the way-points using two or more separate Lissajous curves having different number of way-points corresponding to varying radii of the structure. Fig.6a has a single curve while Fig.6b has two Lissajous curves having the lower one with 400 way-points and 100 way-points in the upper Lissajous curve.

III. Controller

Drones move along the 3-D way-points generated by the Lissajous curves method, as demonstrated in Fig.3. The drones are also, additionally, required to collect data at each way-point.

The position and attitude controller developed facilitates both tracking and collection of data. For the drone in simulation, ARdrone 2.0, PD controllers were designed for position, attitude, and data acquisition.

$$e_x = X - X^* \tag{19}$$

$$e_\theta = \theta - \theta^* \tag{20}$$

$$e_{da} = P - P^* \tag{21}$$

where X, θ ,and P represent the position, attitude and pixels inside bounding box respectively and X^*, θ^* ,and P^* represent the corresponding ideal states.

The defined control laws are:

$$u_x = K_{px} e_x + K_{dx} \dot{e_x} \tag{22}$$

$$u_\theta = K_{p\theta} e_\theta + K_{d\theta} \dot{e_\theta} \tag{23}$$

$$u_{da} = K_{pp} e_{da} + K_{dp} \dot{e_{da}} \tag{24}$$

where u_x, u_θ and u_{da} are the control inputs provided to the drone. The controller gains obtained through trial and error tuning is presented in Table.1.

Table 1: Controller Gains

Controller	PD gains
Position	K_{px} =2.0, K_{dx} =2 $\times 10^{-3}$
Attitude	$K_{p\theta}$ =0.4, $K_{d\theta}$ =4 $\times 10^{-3}$
Data Acquisition	K_{pp} =0.2, K_{dp} =2 $\times 10^{-3}$

The various simulations in the ROS-Gazebo environment to carry out the coverage path planning with way-points generation using Lissajous curves are elucidated in the next section.

IV. Simulations

Initially, a two-dimensional on-ground simulation was carried out. Apart from control, a provision for stopping, turning

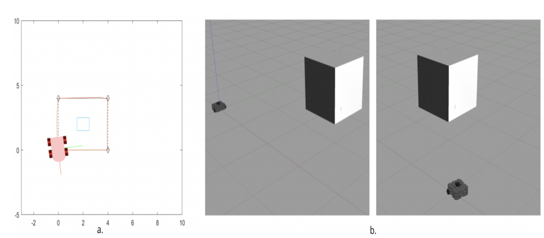

Fig. 8. (a) The trajectory followed by the turtlebot. (b) The Gazebo shots captured at the first corner during data collection.

to the structure, and collecting data at each way-point. The simulation was carried out using Turtlebot3, and the structure was cube of 1m side length. The objective of the exercise was to facilitate the adjustment of position from structure surface-based of the number of pixels captured by the camera inside a bounding box determined around the cube structure.

Fig. 9. Images saved in the 2D path following problem at each way point.

The data collection takes place after the number of pixels of the cube inside a generated bounding box in real-time is in the desired range. This constraint makes sure that the distance of the turtlebot from the structure is in the desired range as well. The same depth perception concept was adopted in the 3D data gathering problem to ensure uniformity in collected images.

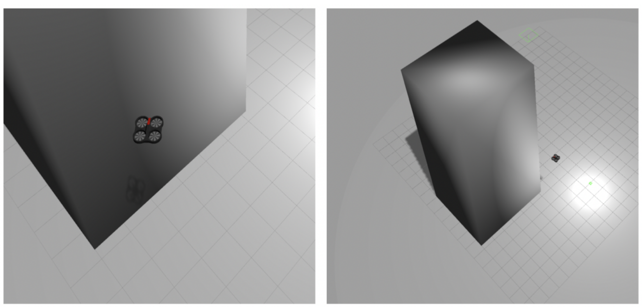

Fig. 10. The ARdrone 2.0 drone in 3D during simulation.

The 3-dimensional coverage path planning is implemented using a drone simulation. The ARdrone 2.0 that is used for simulation is controlled and made to follow the trajectory using PD controllers for both position and altitude. The different trajectories the drone was made to follow are shown below.

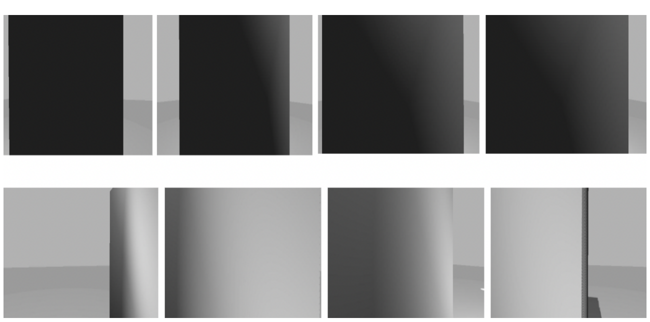

Fig. 11. Images collected in simulation using MATLAB Desktop Prototyping. A total of 105 images are collected corresponding to each way-point, 8 of them are presented above.

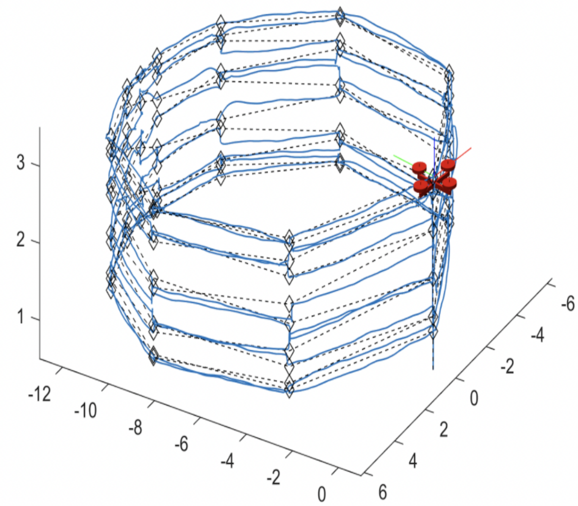

Fig. 12. The trajectory followed by the ARdrone 2.0 drone in 3D along the transformed cylindrical surface

Finally, as performed in the turtlebot simulation, the drone is made to face the structure at each of the way-points and collect visual data. Throughout the process, the drone is stabilized at the altitude using a PD controller. The structure was a large cuboid with 3mx3mx6m dimensions.

The trajectory generated by the Lissajous curves can cover the surface of the entire structure, and at the same time, they can be easily split into multiple drones operations. The division is done such the Lissajous curve time series are not disrupted, and hence it is a very convenient way to plan multi-drone paths.

V. Conclusions

Through this paper, a new solution to coverage path planning is proposed and implemented for 3D structures. Simulation carried out shows the feasibility of this method. The use of Lissajous patterns to generate way-points and trajectories gives us a relatively simple and computationally efficient process to carry out the complete coverage. The simulations are carried out using ROS-Gazebo using tum_simulator with ARdrone 2.0 and Turtlebot as the drive-robot. In the future, optimization of the path with respect to energy expenditure or time and the inclusion of multiple drones to carry out the structural inspection could be implemented to improve the current setup. Moreover, the radius of the enclosing surface used to create the 3D Lissajous curves can be varied with time and height to better conform with the structure. The challenge of way-points moving closer to each other needs to be mitigated by reducing the number of way-points with a decrease in radius. The above-presented methodology can be used for cases that do not require explicit knowledge about the geometry of the structure.

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