Aerial laser inspection of buildings facades using quadrotor

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Abstract

Monitoring is the backbone of any project management task. In construction, where the service or product to be delivered is directly related to human beings, quality assurance reigns supreme in terms of priority and importance. Construction project goes beyond handing over of the building. The upkeep of the building requires continuous monitoring to maintain the safety aspects as well as aesthetic elements of the building including facades and marble constructions. Laser scanning and photogrammetry can be used for inspection and detection of defects, which can be very valuable for preventive maintenance.

We offer to expand the role of the terrestrial laser scanning mechanism, to an aerial inspection and 3D building model generation using quadrotors based on simulations. This will automate the scanning process, increase range of the inspecting device and minimize the time of shifting and setting up the laser or the cameras, especially when operating in difficult site conditions, hence the aim of this paper.

Keywords: quadrotor; aerial building inspection, quality management.

1. Introduction

Three-dimensional technology has invaded the market of imaging. Nowadays, we count several applications where the three dimensional technology is utilized. For example, in medical field, endoscopic manufacturing companies has released a 3D exoscopes, that can give a 3D preview of an organ. In parallel, delayed 3D constructions are used in Cath-Labs and MRI technology. In the entertainment field, 3D films have taken the observer to a new experience that in reality tries to create new impressions, which sometimes transfer the observer from a passive state to an active state.

In light of the continuous success, pioneer companies are investing in integrating 3D technology to other fields. Nowadays, there are many internet service providers that are using the 3D technology to build map applications such as Google, Apple... These applications are accessible to 1.75 billion people, using smart phones. This software is also used for touristic purposes, identifying new places, hiking and most probably for military missions.

The success of these applications hugely depends on the quality of the images. We are dedicating this paper to improve the image quality by achieving better stability of the capturing device. The images taken from the aerial station to generate 3D model can be used to evaluate the condition of the building [14,15]. Facades and marble structures are often affected by climatic conditions. For instance, the aesthetic structures in a humid and hot region as in the Middle East, are more prone to be damaged than in France for example. This requires periodic monitoring of the building to diagnose possible damages. Mostly, laser scanning is used to detect cracks using terrestrial setup. This has limitations in scanning difficult angles, requires time to be transported and setup, in addition requires manpower to perform the tasks.

There are two main approaches used for structure scanning, the photogrammetry and the laser scanning. The first is the technology of obtaining information about the status of an object by analyzing captured images. Mostly, it is implemented in aerial scanning [12,13,15,16,17]. Its accuracy is questionable, however it is being optimized using new machine vision algorithms. Photogrammetry is not optimal for real time model generation as it lacks the digitization process.

In parallel, laser scanning is faster for real time process then the photogrammetry, but the risk of losing the data is high when the resolution is low. It is used for terrestrial scanning due to the altitude limitations. Recently, the terrestrial method is combined with the aerial photogrammetry to achieve better scanning and model generating results [12, 13, 17].
2. Building up case study - Aerial Inspection

Several technologies are used to perform building scanning with different advantages and disadvantages [16]. Optimally, scanning setup has to be portable, mobile, fast processing and cost effective. Table 1 provides a general overview on the techniques used to scan civil structures.

| Method         | Fieldwork                          | Processing                        | Manpower                  |
|----------------|------------------------------------|-----------------------------------|---------------------------|
| Tachometry     | Traversing – 1 day                 | Generating the topographic plan – 1 day | Ideally 4 persons         |
|                | Tachometry – 2 days                |                                   |                           |
| Manned aircraft| Traversing, pre-marking and flight planning – 96 hours | Image scanning and processing – up to 1 month | Ideally 2 pilots and 1 person on the ground |
| UAV            | UAV setup– 20 min                  | Image processing until map production – 4 hours | Ideally 1 person-operator |
|                | Flight – 30 min                    |                                   |                           |

Tachometry method requires more manpower. Level of automation of the scanning process is limited. A dedicated team has to be always on the ground. The mobility of the team is very crucial for the success of the mission. Climate and condition of the field have a direct impact on the required time for scanning and generation of 3D models.

Using manned aircraft improves the processing time. Although it can be successfully used for city scanning, it is impossible to detect defects or damages all around the building. In addition, the manned aircraft is not optimized to do periodic or repeated trips due to the fuel consumption and requires as much manpower as the tachometry method.

Unmanned aerial vehicle is the optimal solution [1,2,3,4,5,6]. Battery operated aircrafts such as quadrotors are small, cheap, maintenance friendly, can perform several flights in the same day with negligible cost and the most important that it has high maneuverability to reach difficult corners.

On the other hand, quadrotors are not stable and have limited flight range. The latter can be resolved by using backup batteries. Stability problem is the most critical part as it can also affect the quality of the captured videos/images [11,14,16].

2.1. Quadrotor dynamics

The aim of this case study is to improve theoretically the stability of the quadrotor while mapping sites and inspecting structures. Recently many researches were carried out to improve the stability and control of unmanned aerial vehicles [8,9,10,11]. In particular, the quadrotor, a miniature vertical take-off and landing rotocraft has occupied the major share in these researches due to its low manufacturing cost. This has made its procurement accessible to many hobbyists and researchers. While taking-off and landing present the most critical phases of any flight, controlling other flight parameters such as stability and titling is also of great importance. The aim will be to get a zero value of Euler angles while hovering and changing position along roll and pitch axis.

Quadrotor dynamics are represented in the form of differential equations. These equations are already known and have been listed in many literatures [7,8,9,10]. Therefore we will skip the generation of equations and limit ourselves to listing them below. The dynamics of a quadrotor are illustrated in the six differential equations.

\[
\begin{align*}
\dot{x} &= -c(\psi) s(\theta) c(\phi) + s(\psi) s(\phi) \frac{T}{m} \\
\dot{y} &= -s(\psi) s(\theta) c(\phi) - s(\phi) c(\psi) \frac{T}{m} \\
\dot{z} &= -c(\theta) c(\phi) \frac{T}{m} + g \\
\dot{\phi} &= \frac{T_\phi}{I_x} \\
\dot{\theta} &= \frac{T_\theta}{I_y} \\
\dot{\psi} &= \frac{T_\psi}{I_z}
\end{align*}
\]
Where, s is Sine function, c is Cosine function, $\ddot{x}$, $\ddot{y}$ and $\ddot{z}$ are the second derivative (acceleration) of the quadrotor position along earth axis OX, OY and OZ respectively and $\ddot{\phi}$, $\ddot{\theta}$ and $\ddot{\psi}$ are the second derivative of the roll, pitch and yaw angles, $I_x$, $I_y$ and $I_z$ are the terms of inertia of the quadrotor while performing a rotational movement, m is the mass of the quadrotor or term of inertia in linear movement and total torque generated per flight regime.

From these equations, we can organize the control system into 4 major loops interconnected:
- OX loop designated for the positioning along OX earth axis. It includes the roll angle loop
- OY loop for positioning along OY earth axis. It includes the pitch loop
- OZ loop for flight altitude
- $\Psi$ loop for yaw

2.2. Quadrotor control – Optimized PID regulators

Optimal control is designed based on the task to be carried out. As far as this paper is concerned, it is important for us to have a stable hovering state and quick maneuvering. A comparative chart below shows the results obtained by different control algorithms.

| Algorithm       | Positioning loop | Euler angles loops |
|-----------------|------------------|--------------------|
| Modular control | 4                | 5.6                | 0.111   | 0.135 |
| LQR             | 3.3              | 7                  | 0.136   | 0.6   |
| PID             | 8.3              | 2.2                | 0       | 0     |
| Fuzzy Logic     | 8.3              | 7.6                | 0       | 0     |
| Average         | 5.379            | 3.6                | 0.0061  | 0.184 |

The results were obtained based on the nonlinearity of the quadrotor. In depth review on comparative analysis between the different proposed control algorithms can be found in [7,8,10]. As a result [7], control scheme with PID regulators proved to be the fastest but with overshoot during the process time as shown in figure1. The control algorithms are simulated taking in consideration displacement of the center of gravity (CG) [18]. Due to the shifted CG, additional accelerations and velocities are sensed by the inertial sensors which have noticeable impact on real time flight.

![Figure 1. Positioning control using PID regulators](image)
It is of great importance to have the smoothest positioning for better capturing quality. Hence, we decided to improve the PID controller using the particle swarm optimization PSO.

Since the overshoot is of concern, the optimization task can be described as follows

\[ F_{Op}(t) = \int_{t_{min}}^{t_{max}} e \, dt \]  \hspace{1cm} (7)

Where \( F_{Op}(t) \) is the cost function, \( e \) is the feedback error and \( t \) is time.

The PSO will tune the gains of the PID controller in such a way to minimize the feedback error within a limited time \([t_{min}, t_{max}]\). The optimization method is a Runge–Kutta solver of differential equation. In particular, it uses six functions to estimate and calculate the fourth and fifth tolerance order. The difference between these solutions is taken as an error. This error estimate is very convenient for adaptive algorithms, such as the use of fuzzy logic to control the process.

The optimization algorithm works as follows: each particle in the swarm has a position. PSO determines the next best position the particle should move to with reference to optimality criterion. The cycle continues until the particle reaches the most optimal position. Consequently, the system moves to the global best value updating the swarm positions to the target. Equation (8) serves as mathematical model for PSO

\[ V_{Op}^{k+1} = \alpha V_i^k + c_1(k+1)\left(best_i - S_i^k\right) + c_2(k+1)\left(gbest - S_i^k\right) \]  \hspace{1cm} (8)

Where, \( V_{Op}^{k+1} \) is the value of the modified velocity, \( \alpha \)-weight function, \( V_i^k \)-current moving speed, \( c_1, c_2 \) are weights, \( best_i \) is the personal best value for the particle, \( S_i^k \) is the current position of the i-th particle and \( gbest \) is the global best position or the target. Optimized results are shown in figure.2.

![Optimization results for PID controller](image)

**Figure 2.** Optimization results for PID controller (A- Results at t= 4.8 s, B- Results at t=10 s.)

### 3. Simulation Results

The optimized PID controller pushed the quadrotor to new stability benchmark conserving its high maneuverability. The obtained algorithm will be implemented to scan the facades and roofs of structures. Civil buildings will be simulated using repeated sequence with different amplitudes. After each period of 5 seconds, the quadrotor has to meet the amplitude at a landmark point. This is supposed to be the optimal angle to capture the roof of the as well as the edges of the building. This will facilitate the creation of 3D model of the structure using triangulation method.
As shown in Figure 3, the optimized control algorithm (red curve) leads for better stability and enhance the capturing quality by meeting the amplitude after a period of 5 seconds. At the same time, flight range is also improved, as the battery is being used with efficiency.

4. Recommendations for real-time flight

Quadrotors can be operated manually, semi-autonomously or autonomously. A manual control allows the operator on the ground to take several captures repeatedly as per his convenience. This can be used to scan single or small group of structures. Semi-autonomous and autonomous flights are more mission oriented. Site mapping is based on global path planning for outdoor scanning and local trajectory generation methods for indoor mapping. For scanning purposes, the operator has to upload waypoints coordinates to the autopilot before taking off using GPS. Autonomous flights can be achieved using visual odometry. This approach does not rely on GPS to generate the trajectory.

In real time flight, semi-autonomous approach is more adequate for scanning purposes. It still permits the interference of the operator but without changing the path of the mission. Commercial remotely controlled semi-autonomous quadrotors have a radius flight range around 50 meters from the operating location because they are dependent on Wi-Fi bandwidth. This can be expanded using satellites to increase the range of cover.

Large sites can be divided into clusters and can be scanned simultaneously by several of quadrotors connected to a central hub, where laser scanning and photogrammetry data are collected and analyzed. The results are used to generate 3D models hence the images can be inspected for defects on site.

5. Conclusion

The obtained results have proven that the quadrotor was able to scan the structures based on desired trajectory and timeframe. The same algorithm can be used to control the quadrotor to scan the facades and different edges of the building, depending on the flight mission designated. While five buildings were scanned 2-dimensionally in 25 seconds, being 5 seconds for each building, the overall time necessary to capture three-dimensionally will take approximately 20 seconds for each building.

In a small town with a 1500 population, the average number of structures is equal to 300. Theoretically, to generate 3D model of the town using triangulation method will consume almost 2 hours, which is a very reasonable time. With an average of 6 hours scanning, the quadrotor can capture minute details, difficult to reach corners, landmarks and defects.

In light of the aforementioned analysis, we believe that the quadrotor can be of a great assistance in building inspection tasks.
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