Inspection of Flyover Bridges Using Quadrotor

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ABSTRACT

Unmanned Aerial Vehicle (UAV) is a military product used extensively in the last decade. The successful outcome has expedited the migration of this technology to the civil market. Nowadays, UAVs can perform photogrammetry, inspection of civil buildings, delivering goods and assisting in rescue missions. The results depend on multiple factors, such as identification of flight mission, choice of UAV type and control algorithms. There are various types and sizes of UAV. The quadrotor is the one of most affordable and manoeuvrable system but it lacks stability. Therefore, we are discussing in this paper how to improve the stability of the quadrotor, while performing routine bridge inspections.

Keywords – Quadrotor, Site management, Structure inspection, particle swarm optimization

1 Introduction

The options for inspecting locations above the ground are quite limited. Ladders and ropes are being used to inspect a height of 10–15 meters. The risk involved in using such methods is quite high: in England and Wales 2011, 17,590 people died due to accidents [4] (Mortality Statistics, 2011). From the grand total, falls occupy a share of 3,885 deaths, where 693 cases tagged as falls from stairs and steps. The provisional figure for the number of workers fatally injured in 2013/14 is 133, and corresponds to a rate of fatal injury of 0.44 deaths per 100 000 workers. Figure 1 shows fatal injury statistics for workers between 1994 and 2014. Due to safety implementations in 2014, percentage of fatal injuries dropped by 19%: comparing with the average for the past five years. The latest rate of fatal injury of 0.44 compares to the five-year average rate of 0.56 [12] (Statistics on fatal injuries, 2014). In the United States, 160 people were killed and 17,000 injured due to falls from ladders.

Referring to the fact that the first aim of robotics is to substitute human beings in dangerous tasks, we suggest implementing robotic concepts for inspection of flyover bridges.

Inspection from manned rotorcraft is possible but is not cost-effective for such preventive maintenance tasks. Besides, it is only suitable in non-urban and open environments. In recent years, we have seen significant advances in miniature vertical and take-off systems (VTOL), in particular, quadrotors. This miniature rotorcraft is known for its high maneuverability and for its non-stability and short flight range. Driven by the development in power electronics, MEMS and NEMS actuators and sensors and microcontrollers, quadrotors became more energy efficient, more stable. The low-cost, sufficient payload and flight endurance to carry out inspection missions [11,13, 15, 18,19] can recommend the integration of the quadrotor in performing bridges inspections.

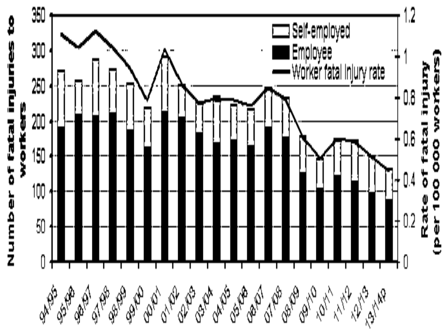

Figure 1- Fatal Injury Statistics for workers between 1994-2014

Hence the aim of this paper is to use autonomous quadrotor to inspect flyover bridges interconnecting multiple cities and locations as part of periodic preventive maintenance (Figure 2). This can be done by tracking assigned waypoints and recording videos in order to detect possible defects and cracks in the construction. In our point of view, automating this task can reduce the number of accidents and contributes to optimized resource usage: i.e. instead of sending multiple groups to inspect multiple locations, it is sufficient to analyze the photos and send the technical team to an assigned spot. We assume that the automation of preventive maintenance will have an impact on reducing fatal injury of workers by minimizing their “unnecessary exposure” to the risk source. The other advantage of using UAV is the possibility of conducting the inspection even during peak-times and traffic. To emphasize more on the importance of these inspections, we give the example of Indonesia consisting of 13,466 islands, where bridges are the only terrestrial connection between different locations. Another important usage for UAV inspection can be recommended while maintaining the French Milau Viaduct bridge, being the tallest in the world with 343 meters and the Russian Russky bridge in Vladivostok 320 meters hanging above the water.

In order to achieve good substitution of the human-inspectors, the quadrotor should be reliable enough to finish the task without failure. This can be reached using optimized control systems. Moreover, the quality of the photogrammetry is directly related to the position of the quadrotor. Hence it is of great importance to achieve the ultimate stability of the quadrotor.

Figure 2- Flyover bridges “Spaghetti”

2 Related Work

Safety of personnel is mandatory as per the labour laws worldwide. Implementing them is part of the workers right. Robots can substitute human being in dangerous tasks but their acquisition is questionable financially. With the new development in technology, robots became cheaper and they are implemented more frequently in civil field. Researchers launched a variety of special robots for vertical infrastructure inspection. Typically, these robots are inspired by the creatures and their type of movement: sliding, swinging, extending, flying and jumping. A new-sophisticated field has born: the Bionics. For instance, The StickyBot has a hierarchical adhesive structure to hold itself on any kind of surface [5], the climbing RiSE V3 robot is designed for high-speed climbing of a uniformly cylindrical structure, such as a telephone or electricity pole [2]. The efficiency of these robots was satisfactory but still their acquisition is not financially justifiable.

Quadrotors are a good alternative for the climbing robots; they are cheaper and more service friendly. An autonomous quadrotor is not Wi-Fi dependent and can fly for longer range. Also, it can carry several sensors due to the new development in nanotechnology. Nowadays, quadrotors can be equipped with multiple high definition cameras, digital and auto calibrated. It has enough internal storage to capture long videos and necessary position sensors that assist in achieving better flight control.

3 Case Study

The efficiency of using quadrotors to perform inspection tasks was analyzed in several literatures. For instance, [11,15,19] simulated autonomous quadrotor inspection for high-rise structures. In a related matter, unmanned quadrotors are more frequently “supervised” [14,16,17].

In this paper, we offer the autonomous flight approach. We assume that a full-robotized quadrotor can achieve better results in terms of minimizing human-resource usage.

To achieve an autonomous flight, we suggest dividing the case study into 2 parts: path planning and flight control. Path planning defines flight mission and trajectory coordinates. The flight control is the design of position regulators to track the generated trajectory.

There are two general approaches of path planning: global and local. In the first approach both the flight mission and coordinates are known to the autopilot prior to flying. The local approach consists of generating trajectory coordinates on the spot by analyzing different optimization cost functions [22]. For inspection purposes, we already know the location of the bridges. Therefore, the task will consists of tracking waypoints assigned to the autopilot prior to its takeoff using GPS.

Hence we will concentrate more on the control algorithm since the GPS trajectory generation is self-explanatory.

3.1 Control Algorithm

Many papers were published to analyse, develop and recommend control approaches [20]. The quadrotor motion is described by 6 differential equations. Although it has 6 degrees of freedom, it can perform only 4-flight regimes: roll, yaw, pitch and hover. The first three are rotational movements: the change in their values leads for 2D displacement of the quadrotor (fixed XOY earth axis). Hover is the fact of flying vertically along the altitude axis (OZ) [21].

Quadrotor has a non-linear model, although it was simplified in many literatures to linearity. We will be sticking to the nonlinear approach while modelling the quadrotor. Besides that, we will consider the fact of shifted centre of gravity in all the control loops. This factor was proven to be essential to simulate flights and design reliable controllers [3,19]

The quadrotor dynamics can be represented as follows:

$$\ddot{X} = (sin\psi sin\varphi + cos\psi sin\theta cos\varphi)\frac{U_1}{m};$$
$$\ddot{Y} = (-cos\psi sin\varphi + sin\psi sin\theta cos\varphi)\frac{U_1}{m};$$
$$\ddot{Z} = -g + (cos\theta cos\varphi)\frac{U_1}{m};$$
$$\ddot{\phi} = \frac{I_{YY} - I_{ZZ}}{I_{XX}}qr - \frac{J_{TP}}{I_{XX}}q\Omega + \frac{U_2}{I_{XX}};$$
$$\ddot{\theta} = \frac{I_{ZZ} - I_{XX}}{I_{YY}}pr - \frac{J_{TP}}{I_{XX}}p\Omega + \frac{U_3}{I_{YY}};$$
$$\ddot{\psi} = \frac{I_{XX} - I_{YY}}{I_{ZZ}}pq + \frac{U_4}{I_{ZZ}};$$

Where, sin is *Sine* function, cos 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_{XX}, I_{YY} and I_{ZZ} are the terms of inertia of the quadrotor while performing a rotational movement, *p*, *q* and *r* are the angular speed of the quadrotor in the body axis, m is the mass of the quadrotor or term of inertia in linear movement and U_i is the total torque generated per flight regime (1- hover, 2- roll, 3- pitch, 4- yaw). From these equations we can organize the control system into 4 major interconnected loops:

- *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;
- *Ψ* loop for yaw control.

Although in many cases, heuristic algorithms were ruled out, due to the time consumption needed to regulate the position, we are proposing fuzzy logic controllers (FLC) to maintain the quadrotor in the desired position [6,7] taking into consideration the factor of shifted centre of gravity from its geometric ideal position. The inputs of the FLC *e(t)* and *de(t)* are the deviation of the quadrotor from the proposed trajectory and its derivation per time. They are represented using triangular membership functions as shown in figure 3 and 4. The output of the FLC is also 5 triangular membership functions figure 5.

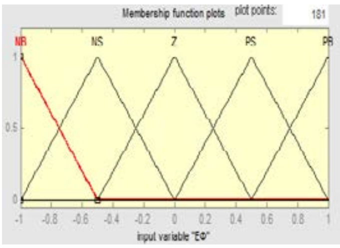

Figure 3. Membership function for input “e(t)”

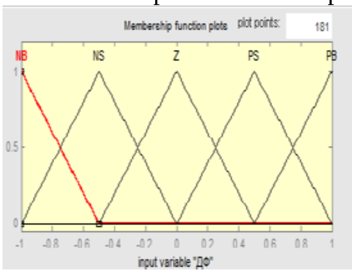

Figure 4. Membership function for input “de(t)”

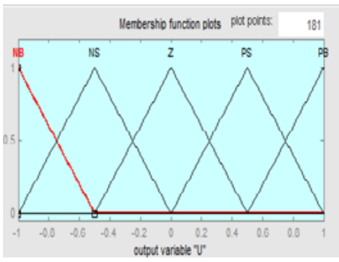

Figure 5 - Membership function for fuzzy regulator output

The trick in such controller is how to set up the linguistic rules for input and output.

We fine tuned the rules by using the resulting graph (figure 6) for the function *de(t)=f(e(t))*, where *e(t)* is the deviation in position of the quadrotor with reference to the desired trajectory and *de(t)* is the variation of the deviation.

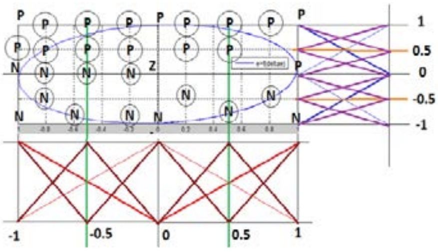

Figure 6- Resulting Graph *de(t)= f(e(t))*

Using the graph in figure 6, we assign the following labels for the numeric values: Negative big (NB) =-1, Negative Small (NS) = -0.5, Zero (Z)=0, Positive Small (PS)= 0.5 and Positive Big (PB) =1. As a result we obtain the linguistic rules listed in table (1). A linguistic rule defines the output of the fuzzy controller based on discrete logic (i.e. if *e (t)*= **NB** and *d(e(t)*= **PB**, then the output is **Z**). the graphical representation of the linguistic rules is illustrated in figure 3.

Table 1: Fuzzy rules

de / *e*	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NS	NB	NB	Z
NS	NS	NS	NS	Z	NS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PS	PS
PB	Z	PB	PB	PB	PB

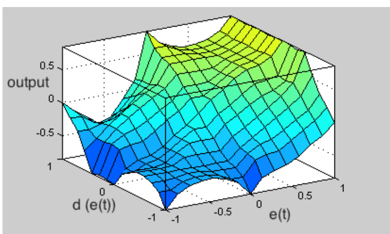

Figure 7- Graphical Representation of the linguistic rules

The results of controlling the quadrotor using FLC are shown in figure 8.

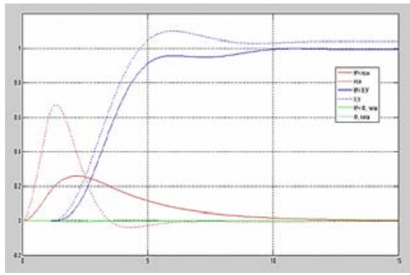

Figure 8- Results of implementation Fuzzy Logic Controllers. Horizontal axis – time [sec], vertical axis position [m] and rotation [°/s]

The thick and doted lines in figure 8 illustrate the FLC and the average of simulation results obtained in other literatures [6,9,10,21,23,24,25]. Blue curve is for linear movement, red is for the yaw angle and green is for the pitch and roll angles. The simulation results are obtained taking into consideration the factor of shifted centre of gravity in all the control loops. It is very important to calculate the moment of inertia according to the centre of gravity for a free-rotating object around the altitude axis [19,23]. Ignoring this factor can produce supplementary acceleration and moments on the axis of the gyroscope, which have to be compensated by the control system. The new moment of inertia can be found using Huygens-Steiner parallel axis theorem.

3.2 Optimization

The proposed fuzzy controllers were able to maintain the quadrotor in the desired position. In comparison with different control algorithm such as LQR [1,9] sliding mode control [10], PID controllers [6,8], the control process seems to be slower but more stable. To improve the speed of the process while maintaining the desired stability, we suggest optimizing FLC using particle swarm optimization method PSO. It is based a Runge-Kutta solver of differential equation. In particular, it uses six functions to estimate and calculate the fourth and fifth tolerance order. The aim of the optimization is to tune the PID gains of the fuzzy controller in-real time flight by minimizing the optimization function. The functional diagram is illustrated in figure 9.

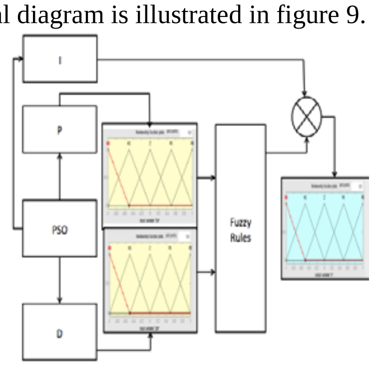

Figure 10- Tuning FLC gains using PSO

The optimization task is described by cost function $F_{optim}(t)$, that we aim to minimize.

$$F_{optim}(t) = \int_{min}^{max} e^2 t.dt \quad (7)$$

Where e^2 – is the square value of the position error with reference to the desired position, t is the time.

The particle swarm algorithm works as follows: the size of swarm population is 50. The algorithm 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 called global best. Consequently, the system moves to the global best value updating the swarm positions to the target. Equation (8) serves as mathematical model for PSO

$$V_{optim}^{k+1} = wV_i^k + c_1(k+1)(pbest_i - S_i^k) + c_2(k+1)(gbest - S_i^k) \quad (8)$$

Where, V_{optim}^{k+1} is the next optimal speed value, w-weight function, V_i^k-current moving speed, c_1, c_2 are weights, $pbest_i$ 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. The results obtained from optimizing the fuzzy logic controllers are shown in Figure 9.

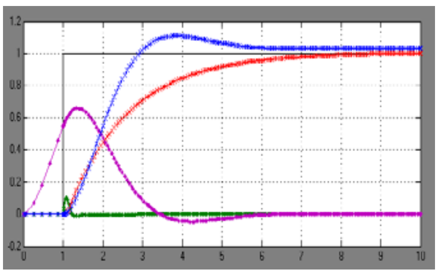

Figure 10- Results of implementation Optimized Fuzzy Logic Controllers.

In figure 10, horizontal axis – time [sec], vertical axis position[m] (red curve XY position, blue curve-altitude) and rotation (green curve- pitch, roll, purple curve- yaw) [°/s]

We can clearly notice that the linear X, Y (red curve) position in figure 7 is optimized in comparison with the same results in figure 6. The simulation shows better stability and quicker processing time reduced to 5 seconds in figure 7.

3.3 Real-time sensors readings

The control algorithm was tested in real time to track waypoints. The results are represented in figures 8,9 and 10. They show the readings of the ultrasound altitude meter, the gyroscope and the accelerometer respectively.

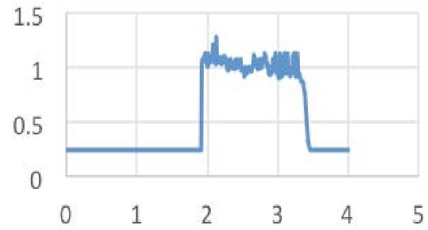

Figure 9- Ultrasonic sensor readings while tracking desired waypoints
X –axis: time (s), Y-axis: attitude (m)

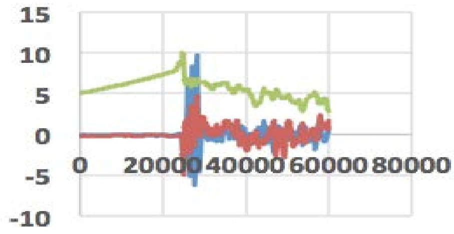

Figure 10- Gyroscope readings while tracking waypoints
X-axis: times (s), Y-axis: orientation (degree)

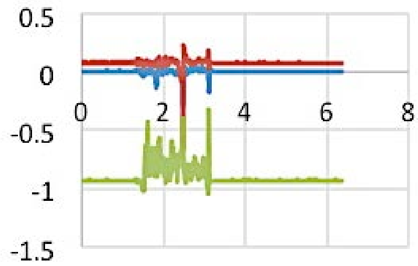

Figure 10- Accelerometer readings while tracking waypoints
X-axis: times (s), Y-axis: linear acceleration (m.s^{-2})

4 Conclusion

The optimized control algorithm was also tested to track waypoints assigned to the autopilot without using GPS. This task was performed using additional visual odometry algorithm. The flight coordinates are acquired by converting the pixel coordinates to metric. The combined algorithm was tested for 2D trajectory. The results are shown in figure 11 and 12 for X and Y axis accordingly.

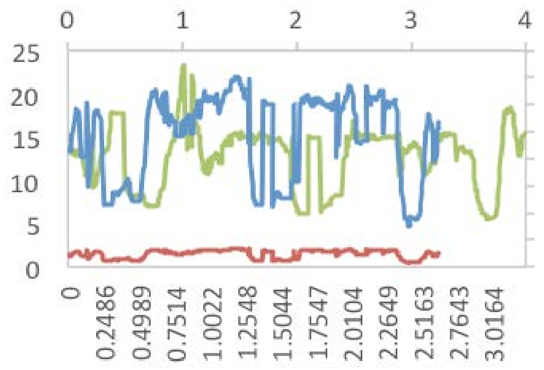

Figure 11- Tracking Visual Odometry output Xp
Top axis- time (s), bottom axis- metric X coordinates (red curve), right axis- orientation in pixels (green curve), left axis pixel coordinates (blue curve)

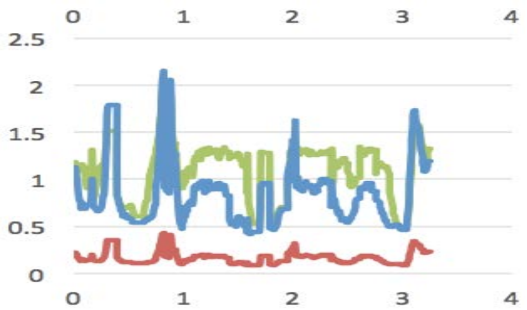

Figure 12. Tracking Visual odometry output Yp
Top axis- time (s), bottom axis- metric Y coordinates (red curve), right axis- orientation in pixels (green curve), left axis pixel coordinates (blue curve)

The results in figure 11 and 12 show that the control algorithm was able to track the desired input generated by the visual odometry algorithm, taking into consideration that conversion factor between the pixel and metric coordinates.

Our future plan is to implement the combined algorithm to perform 3D flight including changes in altitude values.

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