THE RESEARCH OF THE PLATFORM FOR BRIDGE VISUAL INSPECTION BASED ON QUAD -ROTOR AIRCRAFT

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The visual inspection is an important measure and one of the basic steps to discover the structural problems of bridges. However, it is necessary to be close to the object in order to discover a crack less than 0.2 mm in a building reaching a length of hundreds of meters or dozens of kilometers. Modern bridges have various structures and their surroundings are complex so it is difficult to inspect visually. Vertical take-off and landing (VTOL) quad-rotor unmanned aerial vehicles can fly in various postures such as hovering, forwarding, crabbing, and backing. Because they have a good vision and the ability to approach closely to buildings, researchers have paid much attention to them. This paper discusses the problem of bridge visual inspection and clarifies why the bridge visual inspection with quad-rotor unmanned aerial vehicles has an extensive application prospect. At the same time, this paper also explores how to improve quad-rotor unmanned aerial vehicles to fit it for bridge visual inspection and do some preliminary indoor experiments to test the feasibility. From the results of these experiments, quad-rotor unmanned aerial vehicles are suitable for the bridge visual inspection perfectly. The end of the paper summarizes the challenges of using quad-rotor unmanned aerial vehicles in the bridge visual inspection.

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ABSTRACT: The visual inspection is an important measure and one of the basic steps to discover the structural problems of bridges. However, it is necessary to be close to the object in order to discover a crack less than 0.2 mm in a building reaching a length of hundreds of meters or dozens of kilometers. Modern bridges have various structures and their surroundings are complex so it is difficult to inspect visually. Vertical take-off and landing (VTOL) quad-rotor unmanned aerial vehicles can fly in various postures such as hovering, forwarding, crabbing, and backing. Because they have a good vision and the ability to approach closely to buildings, researchers have paid much attention to them. This paper discusses the problem of bridge visual inspection and clarifies why the bridge visual inspection with quad-rotor unmanned aerial vehicles has an extensive application prospect. At the same time, this paper also explores how to improve quad-rotor unmanned aerial vehicles to fit it for bridge visual inspection and do some preliminary indoor experiments to test the feasibility. From the results of these experiments, quad-rotor unmanned aerial vehicles are suitable for the bridge visual inspection perfectly. The end of the paper summarizes the challenges of using quad-rotor unmanned aerial vehicles in the bridge visual inspection.

1 INSTRUCTIONS

By the year of 2009, China’s total mileage of highway has reached 3 860 800 km, and the number of highway bridges has amounted to 621 900, making China the country that owns the most bridges according to the latest statistical bulletin of the development of highway and waterway transportation from the China’s Ministry of Transport. Bridges are important highway infrastructures and the construction of them costs much. Their qualities have a direct impact on the safe and quick flowing traffic. Under the circumstance of highway networks, once bridges collapse or are destroyed by accident, it will cause huge economic lose and other damages, exerting an unbearable social effect on modern transportation system, and the situation turns out to be worse especially for large bridges. Thus a higher level of infrastructure structure for important highway and safety of traffic is required.

In order to avoid the potential safety problems in bridge structure, Specification for Highway Bridge Maintenance, a China's transportation industry standard, has developed detailed approaches for Bridge maintenance and management, in which visual inspection of bridge is one of the important means and basic steps to identify problems. However, the diversity of modern bridge structures and the complex surroundings make it difficult to implement visual inspection. The reasons are as follows: (1) Bridges are buildings across obstacles, such as rivers, valleys, roads, railways, etc; (2) Clear height and clear span of bridges vary widely. The former can range from one meter to hundreds of meters, and the latter from several meters to thousands of meters; (3) The objects of bridge visual inspection include not only bridge floors but also piers and the bottoms and sides of girders; (4) In order to discover the tiny crack less than 0.2 millimeter in a huge building as long as hundreds of meters or dozens of kilometers (for example, Hangzhou Bay Bridge), close approach to the observed object is necessary.

However, the most difficult is that the test objects are usually difficult to reach. With advances in science and technology, bridge inspection vehicles can help bridge inspectors to have a more detailed examination of the bottoms of bridge girders. But there are disadvantages for using bridge inspection vehicles. (1) Renting bridge inspection vehicles costs much, about 10,000 to 20,000 Yuan or so per day on average. (It will cost more than 5 million Yuan to purchase one bridge inspection vehicle.) (2) For the traffic safety, traffic control measures must be taken since the bridge inspection vehicle is relatively large, occupying one traffic lane and a half. (3) Inspecting efficiency is low, for it takes time to readjust the inspection vehicle for the inspection of every span, as shown in Figure 1. (4) Some places, such as towers, arch bridges across valleys or rivers and so on, are inaccessible for the inspection vehicle, and there are many blind spots for inspection. (5) It will constitute a danger to personal safety of users under certain circumstances like traffic accidents, extreme weather events of thunderstorm or typhoon etc.

Figure 1 Bridge Inspection Vehicle.

In addition, the 5.12 Wenchuan earthquake in Sichuan Province has brought a lot of reflection on China’s transportation. The highway traffic was completely cut off and bridge inspection vehicles were not available in the earthquake zones at that time. However, the government was in dire need of being aware of the extent of the damage to the local highways and bridges in order to work out a scientific strategy to deliver relief supplies. Under this circumstance, the measures for bridge visual inspection were back to the primitive state of hiking and using telescopes, thus the reliability totally depends on inspectors’ experiences and perception.

Although Wenchuan earthquake brought a catastrophe to Sichuan Province, the relief action by air from the government and the application of unmanned aerial vehicles (UAV) has inspired experts. If UAVs can be applied to bridge visual inspection with more sophisticated technologies in this field, these UAVs can be available both for daily use and in emergency after a disaster, avoiding bridge inspection vehicles' limitation. There is no doubt that UAVs will become a more ideal inspection platform than bridge inspection vehicle.

The second part discusses and analyzes why use quad-rotor UAVs and the recent research progress. The third part discusses and analyzes the structural model of the quad-rotor UAVs suitable for bridge visual inspection according to the characteristics of bridge visual inspection. The fourth part customizes the traditional quad-rotor according to the structural models of quad-rotor UAVs designed in Part 3 and verifies the feasibility through the preliminary indoor test. The fifth part analyzes the problems of the application of quad-rotor UAVs in the bridges visual inspection

2 QUAD-ROTOR UAVS AND THE RECENT RESEARCH PROGRESS

The vertical take-off and landing (VTOL) quad-rotor UAVs have a higher research value than the fixed wing UAV due to the following advantages: VTOL quad-rotor UAVs can adapt to various environments; VTOL quad-rotor UAVs can take off and land by their own with a more sophisticated intelligence; VTOL quad-rotor UAVs can fly in many ways like hovering, forward flight, sideward flight and backward flight.

Although the technology of unmanned rotor-fixed aerial vehicle (monoplane), the huge rotor above the vehicle is the problem for the visual inspection of the bottom of bridge. Firstly, it blocks the view from vertically up, which results in that the camera cannot see the situation of the bottom of the bridge. Secondly, the huge rotor make it impossible for camera to approach closely to the bridge, which make it more difficult and even impossible for the inspection of cracks. Quad-rotor aerial vehicles provide a good view in the midlle. There is no blocking whether from above or from side, which is an important reason to choose it in the bridge visual inspection.

Now many researches on quad-rotor aerial vehicles are being conducting worldwide. They focus on the autonomous navigation of quad-rotor UAVs. The influential researches are the Mesicopter Project of Stanford University, the UAV Swarm Heakth Mananement Poject of MIT, the Starmac Project of Stanford University, the 2 projects of quad-rotor aerial vehicles in Cornell University, the X-4flyer Poject of ANU, the GTMARs Project of Georgia Institute of Technology, the quad-rotor project of the School of Electrical and Computer Engineering of University of British Columbia and the remote quad-rotor project of American Draganflyer innovations corporation.

The researches on small quad-rotor UAVs in the world focuses on three aspects: the autonomous navigation based on inertial navigation, the autonomous navigation based on vision and the systematic scheme of autonomously navigated vehicles. Considering image recognition technology is used in the bridge visual inspection, the autonomous navigation based on vision will be an important aspect of the development of bridge visual inspection. The Berkeley Aerobot Research team (BEAR) of University of California at Berkeley and the Aerospace Robotic Lab of Stanford University are famous for their achievements in this field.

Sharp C.S. and others from BEAR provided a method based on the relation of projections to speculate the location and posture of a UAV by using point information. This method uses the point in the three-dimensional space to from a corresponding image point on the image surface through perspective projection. When the location of the point is known, the loaction of the image point is decided by parameters that reflect the location and posture of the camera. Through choosing any four feature points on the ground sign that ant three points are not in a straight line and solving these equations, the parameters of the location and posture of the camera can be acquired and thus the parameters of the location and posture of the aerial vehicle can be acquired.

Rock S.M. and others from the Aerospace Robotic Laboratory of Stanford University integrated the application of the Carrier-Phase Differential Global Positioning System (CDGPS) and the binocular vision system. They recognize the image of ground sign through the binocular vision system. The color-based object recognition method is used to process the images acquired by the left camera and the right camera and the two differential images are used to locate the projection of the objuect. The parameters of the aerial vehicle’s relative loaction can be speculated through the basic triangulation. Although the calculation of this method is simple, the method must involve two camera in the vehicle and double the amout of computation of processing images. So the image information acquired by the camera in the vehicle must be transmitted to the ground control station via wireless network to be processed. And then the parameters of the location and posture of the aerial vehicle are speculated and are transmitted back to the control system in the vehicle via wireless network. This limit the application in micro and small aerial vehciles.

All the structures of bridges have specific coordinate gemetry design drawings. If quad-rotor UAVs can take full advangtage of the characteristics of the bridge structures for the vision-based navigation, the working load of UAVs can be reduced and the working efficiency can be improved.

3 THE BRIDGE APPLICATION ORIENTED MODEL OF QUAD-ROTOR UAVS

The current researches on quad-rotor UAVs are using the simple mechanical prototype of a quad-rotor UAV shown in Figure 2 to test, model and simulate. Taking long-range videos and photos through quad-rotor UAVs has been put into commercial use. The quad-rotor UAVs must have the ability to stay on the surface of the inspected building for the bridge visual inspection. The reason is that the bridge maintaining and managing personnel pay more attention to the width of a crack while inspecting the cracks in the concrete surface. For inspectin the width, the following requirements must be meeted: The resolution of the taken images must be high enough to recognize cracks moren 0.1 mm; the vehcile must be close to the surface of buildings because ordinary cameras are used dut to the poor load capacity of the quad-rotor UAVs.

If the vehicles must be close to the surface of bridges, the UAVs in Figure 2 must be upgraded to avoid crash or destruction due to loss of control and other safety problems. At the same time, to make quad-rotor UAVs suitable for bridge visual inspection, this paper considering two ways to realize it: Firstly, the quad-rotor UAVs can fly closely to the surfaces of bridges; secondly, a graduated ruler is added. While the UAVs are close to the surfaces, the graduated ruler is close to the surfaces. Thus the cracks‘ images with graduation can be taken while inspecting the cracks on the bottoms of briges near the surface. It is very convenient to speculate the width of cracks in the bridges.

Figure 3 shows the improved physical structural model of the quad-rotor UAVs in the bridge visual inspection. Compare to that in Figure 2, the model is added three parts: firstly, as shown on the left of Figure 3, the sticks connecting the center and the four rotors are extended and are linked by ringlike elastic material. The protective round circle must be beyond the rotors to ensure that the rotors will not bump into the building. Secondly, as shown on the right of Figure 3, four vertical poles are added on the connection sticks. The height must be beyond the height of the rotors to avoid damge when the vehicle approach the surfaces of buildings. Thirdly, as shown on the right of Figure 4, a gradauted ruler is added at the diagonal lines of the four vertical poles.

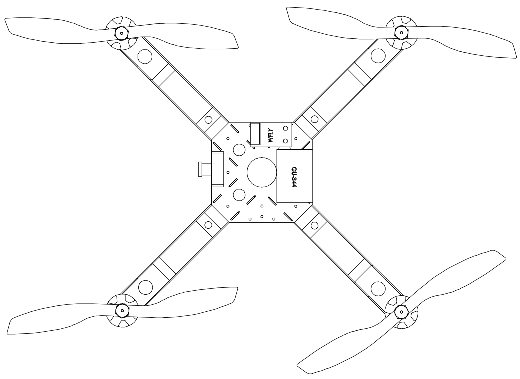

Figure 2 A simple mechanical prototype of a quad-rotor UAV.

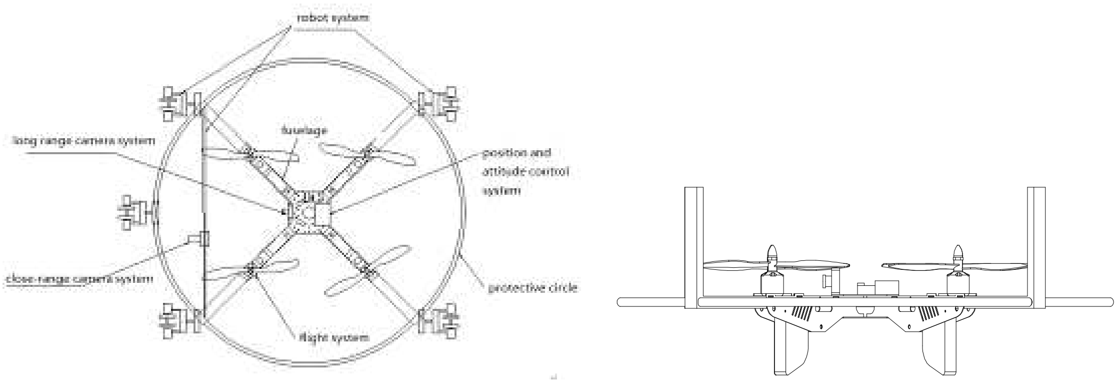

Figure 3 The mechanical top and side view of a quad-rotor UAV with protective accessories.

4 THE VISUAL INSPECTION EXPERIMENT OF THE QUAD-ROTOR UAV

To verify the change of the quad-rotor UAV in Part 3 and the method of visual inspection, a upgraded model from the model of GAUI (a Taiwanese brand) 330 brought by the research group is shown in Figure 4. Considering the bridge visual inspection maily include two parts, two experiemts are conducted here. The first is the experiemt of attaching the UAV to the bottom of a building. As shown in Figure 6, the second is the feasibility test of the upgraded quad-rotor UAV carried out by the research group. After it adheres to the bottom of the bridge girder, the UAV can use its close-range camera system to take photos. The control is very inconvenient because it is operated by man. But it was found through preliminary experiments that the control of UAV changes obviously due to the extra protective accessories and auxiliary equipment, thus it is necessary to re-model and re-simulate according to the new model.

1) The experiment of staying on the ceiling

Figure 4 shows the upgraded UAV for staying on the ceiling

Figure 4 The structure of the upgraded UAV for staying on the ceiling.

As shown in Figure 4, four vertical poles are added outside the four rotors and the height of poles is much higher than that of rotors. The vehcile could stay on the ceiling steadily only by the lift force of the four rotors, which seems that the vehicle is attached to the ceiling. A graduated ruler is fixed on the top of two vertical poles which construct a diagonal line for measuring the width of cracks.

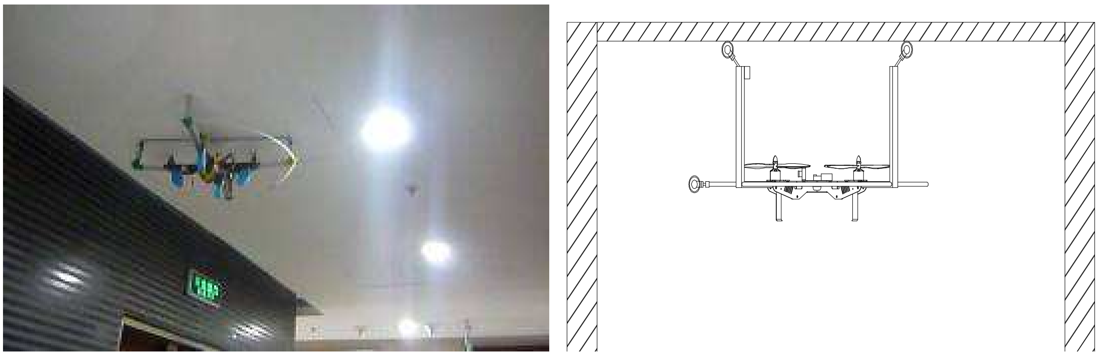

Figure 5 The experiment of staying on the ceiling and the physical model.

Figure 5 is the experiment of the vehicle staying on the ceiling. According to the experiemnt, under condition that the driving force is strong, the stay of the UAV is very steady. A wireless camera with the up view is installed in the middle of the UAV in the figure. Figure 6 shows the image of a crack taken by the camera while the vehicle is staying on the ceiling. The minimum unit of the graduated rular is mm, and the leghth of each graduating line is between 0.1 mm and 0.2 mm. Therefore, despite the resolution of the camera is relatively low (it is only of 360 * 240), it is high enough to measure the crack's width through image if the vehicle can be close enough to the surface of the building as shown in Figure 5.

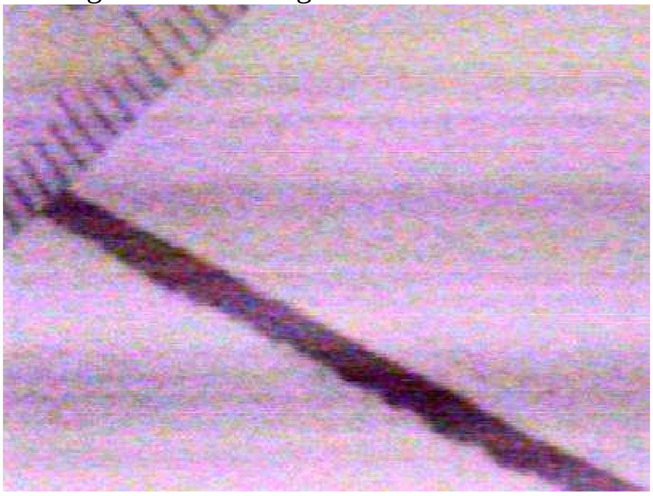

Figure 6 The screenshot of the video taken by the crack inspecting camera in the experiment of the UAV staying on the ceiling.

1) The experimet of the vehicle staying on the side

Figure 7 shows the upgraded UAV for staying on the ceiling:

Figure 7 The structure of the upgraded UAV for staying on the side.

As shown in Figure 7, the two poles in the front of the UAV are lengthened and the protective circle is more protruding. If the vehicle approaches the wall slowly, the two poles and part of the protective circle can form a three poing support system, which lead to a steady posture of staying on the side. But if the UAV approaches the wall too fast, the vehicle will bounce back due to the reacting force and cannot stay on the side.

Figure 8 shows the experiment of staying on the side and the physical model. In the experiment, the posture of staying on the side lasts for about 30 seconds, which is long enough for the taking images for crack inspection.

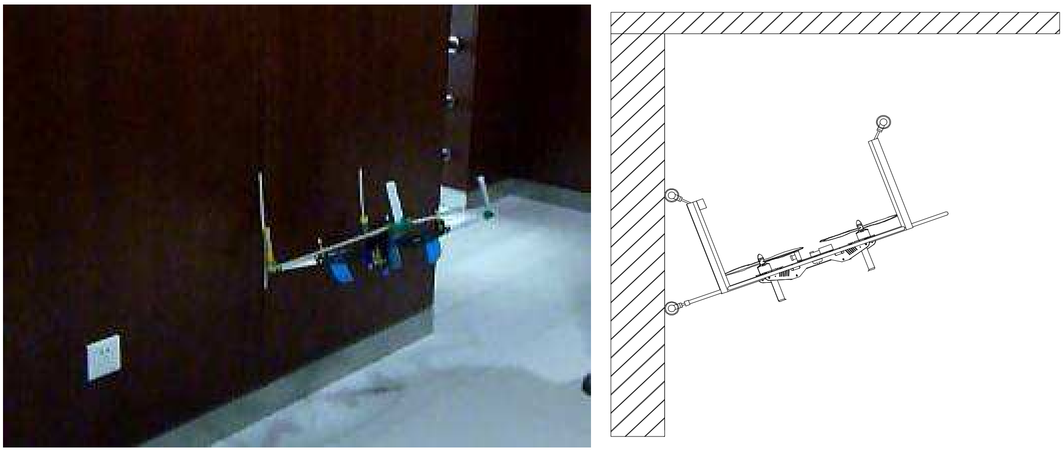

Figure 8 The experiment of staying on the side and the physical model.

The two experiments in this part demonstrate that the bridge visual inspection through the quad-rotor UAV approaching closely to the surface of bridges proposed in this paper is utterly feasible.

5 THE PROBLEMS AND CHALLENGES OF THE APPLICATION OF QUAD-ROTOR UAVS IN BRIDGE INSPECTION

Although the commercial use of quad-rotor UAVs in aerial photography is very mature, there are still many problems and challenges in the extensive application of multi-rotor UAVs in the bridge visual inspection. The main problems are:

1) Autonomous navigation: The current navigation technology of UAVs mainly relies on GPS positioning signals. When the UAV approach tall buildings or fly under bridges, the GPS satellite signal will be screened by the buildings or bridges so that the vehicles cannot receive them. So it is very significant to research the navigation without the help of GPS. This is the key factor for the application of quad-rotor UAVs in the bridge visual inspection. The mature navigation technology will improve UAVs' working efficiency in bridge visual inspection greatly, and lower the requirement of UAV operators to the ultimate extent. Now the autonomous navigation based on vision is the focus of quad-rotor UAV researches, that is, without the help of GPS, digital image processing technology is used to resolve image information and to speculate vehicles' locations compared to bridges and the flying direction in the next move.

2) Flying duration: The flying duration of most quad-rotor UAVs is between 15 minutes to 30 minutes. However, the image acquiring devices in the bridge visual inspection need to work under a nearly static state, which lasts for a long time. Therefore, short flying duration diminished the engineering application value very much for the specific engineering application of bridge inspection.

3) Load capacity: The load capacity of multi-rotor UAVs is now limited. The gross vehicle weight of most UAVs is below 3 kg. The load capacity decides how many inspecting devices can be carried while working. Nevertheless, flying duration and load capacity contradict with each other. It is an important problem to balance the two aspects according to the actual need in the engineering project.

4) Safety: The basic solution to the safety problem of quad-rotor UAVs is to add necessary anti-collision protective devices because the vehicle must approach to the

bridge in the visual inspection. In addition, the surroundings of bridges are complicated and many bridges cross rivers, lakes or seas. It is also a safety problem worth attention to avoid losses and find UAVs when they encounter accidents (for example, strong gale) and lose control.

5) Image recognition technology for concrete cracks: The surface of concrete is very complicate. There are holes of different size, various colors of different concrete frameworks, the chromatic aberration due to different water/cement ratios and the different effects of natural light and shade. All these will disturb the image recognition seriously, thus the error rate is very high. So image recognition technology for concrete cracks is also a problem worth deep research

6 CONCLUSION

The design, research and manufacture of multi-rotor unmanned aerial vehicles is a comprehensive scientific and technical project which integrates many technical achievements including manufacturing technology, structural design, materials engineering, aerodynamics, autonomous flight control and navigation, robotics, image processing, advanced telecommunications, efficient energy, MEMS technology, sensor technology and other high, refined and top technology in various interdisciplinary subjects. The researching and manufacturing process not only solve various problems in the process but also promote the development in many relevant technical fields, which is very meaningful. The project could be regard as an excellent scientific experiment platform for interdisciplinary subjects. Although there are many advantages for quad-rotor unmanned aerial vehicles being used in the bridge inspection, there are problems waiting for solution.

This paper explores the application of quad-rotor UAVs in the bridge visual inspection and improves quad-rotor unmanned aerial vehicles to fit it for bridge visual inspection. From the results of the indoor experiments, the improvement is realistic and feasible.

To sum up, the researches of the bridge visual inspection with multi-rotor UAVs has an extensive application prospect. The researches involve the fusion and integration of many disciplines and the solution to many technical problems. But the engineering application of these research achievements has significant importance to the national economy and disaster prevention and mitigation. The technical achievements can not only be applied to bridges but also various huge buildings such as banks, high-rises, television towers, large stadium.

[1]、Phillip McKerrow. 2004. Modeling the Draganflyer four-rotor helicopter[C], Proceedings of the 2004 IEEE International Conference on Robotics & Automation New Orieans，LA April 2004
[2]、Steven L. Waslander, 2005. Gabriel M. Hoffmann，Jung Soon Jang，Claire J. Tomlin. Multi-Agent Quadrotor Testbed Control Design: Integral Sliding Mode vs. Reinforcement Learning[C]，2005 IEEE/RSJ International Conference 2-6 Aug. 2005
[3]、G. Hoffmann，D.G. Rajnarayan， S.L. Waslander. 2004. The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control(STARMAC)[C]，Proceedings of the 23rd Digital Avionics Systems Conference，Salt Lake City，Utah，November，2004.
[4]、Pounds P.，Mahony R. 2006. Modeling and Control of a Quad-Rotor Robot[C]，In Proceedings of The Australasian Conference on Robotics and Automation，2006.
[5]、Altug E.，Ostrowski J.P.，Taylor C.J. 2003. Quadrotor control using dual camera visual feedback[C]，Proceedings of IEEE International Conference on Robotics and Automation，Taipei，Taiwan，2003，PP.4294-4299.
[6]、Glenn P. Tournier，Mario Valenti，Jonathan P. 2006. How. Estimation and Control of a Quadrotor Vehicle Using Monocular Vision and Moire Patterns[C]，AIAA Guidance，Navigation，and Control Conferenee and Exhibit,21-24 August 2006，Keystone，Colorado
[7]、Bouabdallah S. 2006. Design and Control of Quadrotors with Application to Autonomous Flying[D]，Lausanne，EPFL 2006.12
[8]、Bouabdallah S，Noth A. 2004. Siegwart R. PID vs LQ Control techniques Applied to an Indoor Micro Quadrotor[C].IEEE International Conference on Intelligent Robots and Systems，2004
[9]、Bouabdallah S，Murrieri P，Siegwart R. 2004. Design and Control of an Indoor Micro Quadrotor[C]，Proceedings of the 2004 IEEE International Conference on Robotics & Automation New Orieans，LA April 2004.
[10]、Bouabdallah S，Siegwart R. 2005. Backstepping and Sliding-mode Techniques Applied to an Indoor Micro Quadrotor[C]. International Conference on Robotics and Automation，Barcelona Spain，April 2005
[11]、V. Mistler，A. Benallegue，N.K. M'Sirdi. 2001. Exact Linearization and Noninteraeting Control of a 4 Rotors Helicopter via Dynamic Feedback[C].IEEE 10th IEEE International WorkshoP on Robot-Human Interactive Communication Bordeaux and Paris，2001.
[12]、J.Dunfied，M. Tarbouehi，G.Labonte. 2004. Neural Network Based control of a Four Rotor Helicopter[C].2004 IEEE International Conference on Industrial Technology(ICIT)
[13]、Morel Y，Leonessa A. 2006. Direct Adaptive Tracking Control of Quadrotor Aerial Vehicles[C]，2006 Florida Conference on Recent Advances Robotics，May25-26，2006
[14]、A. Benallegue，A. Mokhtari，and L.Fridman. 2006. Feedback Linearization and High Order Sliding Mode observer For A Quadrotor UAV[C]，Proceedings of the 2006 International Workshop on Variable Structure Systems Alghero，Italy，June 5-7，2006.
[15] 、N. Guenard，T.Hamel，V. Moreau. 2005. Dynamic modeling and intuitive control strategy for an "X4-flyer"[C]，ICCA 05 Budapest hongrie June26-29 2005