UAVs with a Passive Rotating Spherical Shell for Exploration of Infrastructure and Disaster Sites

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学 位 記 番 号	情　博　第　６４７　号
学位授与年月日	平成２９年　９月２５日
学位授与の要件	学位規則第４条第１項該当
研 究 科 、専 攻	東北大学大学院情報科学研究科（博士課程）応用情報科学専攻
学 位 論 文 題 目	UAVs with a Passive Rotating Spherical Shell for Exploration of Infrastructure and Disaster Sites（インフラ点検や災害対応のための受動回転球殻を有する飛行ロボットの研究）
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論 文 内 容 の 要 旨

CHAPTER 1

Unmanned aerial vehicle or UAV is an aircraft without a human pilot onboard. UAVs are developed primarily to take the place of manned aircraft in a mission where it is too dangerous for the human to engage. Likewise, a couple of advantages of using the UAVs attracted the researchers to focus on them that include higher mobility than ground robots and can y above the ground. They are now one of the emerging technology with promising applications to improve the quality of life of the modern society. They have various usage for civilian purposes in the field of agriculture, industry, environment, infrastructure and disaster response. In the area of infrastructure inspection and disaster response, they are becoming very attractive because of their unique capabilities.

Many incidents of collapsed infrastructures that killed several people and created a negative impact on the economy are one of the motivation to develop a UAV system that can perform an efficient and immediate method of inspection to prevent any serious problem. For instance, the part of the ceiling of Sasago tunnel had collapsed which killed nine people, and two others were injured. It is found out that the main reason is due to the degradation of infrastructure. Periodic and immediate inspection of infrastructures like visual checking of cracks and non-destructive testing on the internal condition of structure could avoid any undesirable event. Likewise, looking for a solution on how to save human lives without risking the lives of human rescuers during destructive calamities such as earthquake and tsunami is another motivation. The main problem is that almost all disaster sites are inaccessible by human rescuer as they are dangerous and cluttered. But, the robots especially the flying robot or UAV can take over some of the roles of human rescuers on accessing the disaster sites and perform visual and physical interaction task.

The surrounding of most infrastructure and disaster sites, however, is cluttered and unknown that could make it difficult for the UAV to perform the mission or worst case, it might fail the mission. The cluttered environment is the primary challenge that most researchers are trying to solve and provide an efficient system under a severe condition. One of the main problems is that UAVs are vulnerable to falling plainly because of its exposed propellers. There are methods to avoid the obstacle such as obstacle avoidance and control strategy when losing propeller(s); however, they are not enough to handle the situation in the complex-structured sites. These areas have a lot of blind spots where it too difficult for the operator to control. Also, external disturbances are likely to exist that may exceed the UAV's control response. Two independent research group introduced a novel approach to solving the problem of accessing cluttered environment. They separately presented a concept of passive rotating spherical shell mechanism to be added in the UAV that will protect and keep the UAV significantly stable during a collision with obstacles.

The general objective of this study is to develop two type of system: a UAV with a passive rotating spherical shell for visual exploration and a UAV with two passive rotating hemispherical shells for physical interaction that can be used for infrastructure inspection and disaster response. The focused are design optimization of the system, introduction of a new concept, and utilization of the mentioned systems to a practical application.

CHAPTER 2

The 2nd Chapter of this dissertation presents the design optimization of the UAV with a passive rotating spherical shell for visual exploration and one of its practical application. This system has already been introduced by past researchers but focused mainly on the concept of the mechanism. In this study, an appropriate and optimal design with the consideration of important parameters and conditions based on the certain complex environment is proposed to make it effective in an actual mission. The plan is to improve the performance of the existing UAV with a passive rotating spherical shell so it can be applied in a real mission.

For the optimization part, the specific aims are to maximize the flight capability of the UAV, minimize the weight of the system, and reduce the effect of air drag. The main components of the UAV such as motors, propellers, and battery were reselected to its optimal value to maximize the flight capability without compromising the size of the spherical shell. The spherical shell component specifically the joint was redesigned to reduce the effect of air drag by applying the concept of an efficient aerodynamic shape.

During the design process, the strength and weight of the component were also considered not to get compromised. Moreover, the spherical shell structure was reselected to minimize the weight and further reduce the air drag without compromising the strength of the spherical shell. The increase of the payload capacity and flight time compared to the previous system is the result of the positive outcome of the reselection of UAV's main components. The computational fluid dynamic (CFD) simulation and wind-tunnel experiment revealed a significant reduction of drag force compared to the previous system. Likewise, the actual flight experiment verified the positive performance of the new system in the presence of strong wind. Changing the structure of the spherical shell from 2V geodesic to fullerene type was able to reduce the weight significantly and brought a small contribution to lessening the drag. In general, the new system has improved its payload capacity, flight time, and ability to fly against the strong wind while maintaining the size of the spherical shell as part of the mission requirement before the actual visual inspection of the bridge as compared to the previous system.

For the application part, a close visual bridge inspection is proposed as the practical mission. The main purpose of the close visual inspection of the bridge is to check for any damages such as cracks and rust. The situation in the bridge is precisely a good test condition because of the existence of the complex structure and the frequent presence of strong wind. Prior to the actual mission, the bridge requirement and condition are determined. The required diameter of the spherical shell is determined based on the open gap of the bridge structure. The possible location of damages is being studied to provide an appropriate visual system. In the actual field, the first objective is to fly and traverse into the complicated and narrow part of the bridge to verify its performance. The second objective is to capture close images in the different part of the bridge at the different position. Finally, the people who are the expert on managing the bridge evaluated the performance of the system to further determine the effectiveness of the system in an actual mission on a harsh and complex environment. Before the actual inspection of the bridge, the simulated bridge inspection verified the advantage of passive rotating spherical shell showing no significant disturbance on the UAV's flight attitude and demonstrating the performance of the visual system to capture images on the different section. In an actual visual inspection, the mission was successfully implemented. The visual system was able to obtain images from various areas in the real bridge experiment. The images include a part of the main girder, floor slabs, and bridge shoe, and bridge corner. The use of the UAV with passive rotating spherical shell along with a visual system has shown to be effective for close visual bridge inspection by satisfying the essential mission requirements. The majority of the evaluators (bridge management people) verified that the system only requires a few improvements before its final operation.

CHAPTER 3

The 3rd Chapter of this dissertation presents a new concept of UAV with two passive rotating hemispherical shells for physical interaction and one of its practical application. The idea was brought from the fact that the UAV with the passive rotating spherical shell cannot be completely utilized for physical interaction. The passive rotating spherical shell will eventually cause a self-collision. Any attempt to access the outside of the shell will disturb the rotation of the spherical shell and will compromise the stability of the UAV. One way to address the problem without discarding the idea of passive rotating spherical shell mechanism, considering its immense advantages for a complex environment application, is to cut the spherical shell into two hemispherical shells. As a result, it will provide a gap for the manipulator to access outside the shell without affecting the rotation of the two hemispherical shells. The protection offered by the spherical shell is maintained and retained two-degree of passive rotation enough to secure better stability for the UAV.

The first step to realizing the new concept was to determine the valuable part of the gap unaffected by the passive rotation of the two hemispherical shells. Finding out the usable gap is necessary to know what kind of physical interaction configuration as well as the possible movement of the manipulator. On the other hand, the different rotations of the two hemispherical shells depending on the point of contact of disturbance are analyzed. The cutting of the spherical shell, however, resulted to deformation and deflection. Thus, thorough structural analysis and appropriate mechanical design were implemented. The final step was to develop a prototype and perform a flight experiment to validate the capabilities of the new system such as able to y over the obstacle and able to manipulate without disturbing the rotation of the two hemispherical shells.

Based on the analysis, the location of the valuable part of the gap is along the roll axis (front-back side) of the UAV. It was determined that the appropriate configuration of physical interaction is a frontal type, a perfect setting for the expected practical application. The deformation and deflection were resolved. In particular, the deflection was minimized by introducing the trusses. Several flights affirmed the capabilities of the new system.

A hammer test using the UAV with two passive rotating hemispherical shells is proposed as practical application. For infrastructure inspection, this system is important to determine damage structures that are not visible on the outer surface, for example, hollow space in the concrete wall due to deterioration. The system as well is intended for the target environment that is too cluttered for an ordinary UAV like a complex-structured bridge or partially damaged building. The challenge is to maintain a stable hovering position of the UAV and keep a close distance to the target structure while performing a hammer testing so it can provide useful data from the sensors, such as impact force and sound, needed for further evaluation. Extra subsystems are added to achieve the objective, such as the horizontal actuator and hammer guide. Then the overall system is developed and tested to verify its performance.

The integration of UAV with two passive rotating hemispherical shells and hammering system was successfully implemented. The idea of horizontal actuator and hammer guide found to be effective to obtain appropriate striking position based on the conducted flight experiment. The flight test verified that the UAV with two passive rotating hemispherical shells is a good platform for physical interaction. Though, several future works are required to make a robust system so it can be used in the actual mission.

CHAPTER 4

The 4th Chapter presents the conclusion of this dissertation. In this study, it showed that the design optimization of the system is an important strategy as a primary reason for the success of the actual mission. The visual inspection of the bridge using the UAV with passive rotating spherical shell affirmed that it could provide safe and efficient visual inspection approach to facilitate human inspector. Moreover, the concept of UAV with two passive rotating hemispherical shells showed to be useful for physical interaction task as demonstrated using the hammer testing application. This new concept as an initial approach for physical interaction in a complex environment can lead to several works in the future. In general, it was concluded that both UAV with a passive rotating spherical shell for visual inspection and UAV with two passive rotating hemispherical shells for physical interaction are significant for exploration of a complex environment such as infrastructure and disaster site.

論文審査結果の要旨

我が国では，多くの橋梁が戦後高度成長期に整備され，老朽化に伴って点検修理が必要となっている。法令で定められている近接目視検査や打音検査を行うためには，足場を組んだり，専用車両を使用する必要があり，莫大なコストや長い工事期間が問題となっている。飛行ロボット（ドローン）は，点検作業を遠隔化し，支援することが可能であると考えられ，飛躍的なコスト低下をもたらすと期待されている。

橋梁の床版や桁の撮影には，橋梁の下の狭い空間においてロボットが飛行しながら近接映像撮影やハンマーによる打診を行う必要があるが，橋梁構造体近傍や内部など，空気の流れが複雑になる場合には，安定した飛行が困難である。受動回転球殻機構を持つ飛行ロボットは，機械的に橋梁構造体との距離を一定に保ち，衝突を避けることができることから，この問題へのブレイクスルーをもたらす可能性が高い技術のひとつとして有望視されている。

本研究は，このような橋梁の近接目視検査や打音検査を目的とした受動回転球殻構造をもつ飛行ロボットの機構設計法を明らかにすることを目的としている。すなわち，近接目視検査のためには，球殻の受動回転性能，空気抵抗，重量，強度を向上させる設計法を明らかにし，また，打音検査のためには，球殻が打音デバイスと干渉せず，安全索による牽引を可能とする球殻機構設計を明らかにしている。本論文は，これらの研究成果を取りまとめたものであり，全編４章からなる。

第１章は緒論であり，本研究の背景，目的および構成を述べている。

第２章では，橋梁の近接撮影を行うための受動回転球殻構造を有する飛行ロボットの機構設計法について述べている。全国のコンクリート橋，鋼橋の調査から，桁間に入って検査できるためには，球殻は直径 1.1 m 未満である必要性を導き出している。球殻の構造として，ジオデシック構造，フラーレン構造，それらのエレメントを間引いた構造について，空気抵抗，重量，強度の観点から比較検討し，最適な基本設計を行っている。また，接合部の形状を最適化することで，軽量で空気抵抗を減らすことを可能にしている。これらの知見に基づき, 直径 950 mm, 重量 2.3 kg, 可搬重量 500 g と軽量でありながら，上空からの墜落時にも破壊しないロボットを設計試作している。おもり落下試験，風洞試験，CFD 解析の結果は，この設計法の妥当性を示している。国交省や内閣府 SIP が行った橋梁点検試験に適用した結果は，十分な耐風性，耐久性，飛行制御精度を示し，本研究に基づく受動回転球殻構造を有する飛行ロボットが，橋梁点検に有効であることを実証している。

第３章では，打音検査を行うための受動回転球殻機構を有する飛行ロボットの機構設計について述べている。球殻を分割し，２つの半球が独立して回転できる構造とし，さらにジンバル機構の自由度を１つ減らして本体との相対移動が発生しない箇所を設けている。これによって，半球の切れ目から打音ハンマーを突き出させて検査対象橋梁を叩くことと，ロボットの安全性を確保するための安全索を取り付けることを可能とすると同時に，球殻の受動回転が妨げられず，橋梁構造体に接触して転がりながら移動できるようにしている。本基本設計に基づき試作した飛行ロボットは，模擬環境における試験によって，構造体に接触しながら打音検査が可能であることを実証している。

第４章は結論である。

以上本論文は，橋梁の近接目視検査や打音検査を目的とした受動回転球殻を有する飛行ロボットの機構設計の方法を明らかにしたもので，応用情報科学およびロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士（情報科学）の学位論文として合格と認める。