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Innovative Development of a Flying robot with a Flexible Manipulator for Aerial Manipulations

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***Abstract*—This paper presents an innovative development of a flying robot or an aerial robot, with a flexible manipulator, called the Dexterous Aerial Robotic System (DFTS), for aerial manipulations, especially for inspections and reparations of various structures such as wind turbines, power lines and open gas pipelines, decorations and painting of high industrial chimneys and walls of high buildings, as well as transport and delivery of courier shipments, relocation and manipulation of assemblies and units in inaccessible or dangerous environments. The proposed DFTS consists of two independent but interconnected systems or functional units, which have two main separate functions respectively, including a basic carrying function, and a precise positioning and stabilization function. The system with a basic carrying function is actually the main flying system, the unmanned aerial vehicle (UAV); it is remotely controlled and piloted. Meanwhile, the aerial manipulation platform, called the vertical take-off and landing platform VTOL, which is an active flying platform with 6 degrees of freedom (DOF) is used for positioning and stabilization; and it is attached to the UAV via the soft link. With the use of a long soft link, the problems which are caused by the air turbulent flows generated by the UAV are minimized, and the aerial manipulations of objects are safely controlled and operated. The VTOL which is equipped with a grasping mechanism was successfully developed, prototyped and tested. The experimental results showed that, the developed VTOL can self-stabilize with the inclination angle of being up to 8 degrees.**

***Index Terms*—Flying robot, aerial robot, flexible manipulator, aerial manipulation, unmanned aerial vehicle, UAV, soft robot link, design, product development**

I. INTRODUCTION

With the technological and scientific trends of moving towards Smart Manufacturing and Industry 4.0, there has been an emerging need of developing multifunctional robotic systems and smart solutions for a wide range of industrial applications [1,2, 10-14]. For applications related to aerial manipulations, there have been lots of efforts and studies to develop flying robots or aerial robots. Basically, one aerial robot has two main functional units or systems: the unmanned aerial vehicle (UAV) and the robotic manipulator(s) or robotic arm(s) which have the capability of directly interacting with objects in the surrounding environment [3,4]. The robotic manipulators of the aerial robot are optimally designed for implementing specific functions and industrial applications, including inspections and reparations of various structures, such as wind turbines, power lines and open gas pipelines, decorations and painting of high industrial chimneys and walls of high buildings, as well as transport and delivery of courier shipments, relocation and manipulation of assemblies and units in inaccessible or dangerous environments [3-7].

One of the key challenges to design aerial robots is to dynamically and optimally control the aerial manipulator (s) in which its center of gravity needs to remains unchanged, and the dynamic impacts from the resultant forces and loads need to be minimized during the aerial manipulations. This is more challenging when the additional flying platform with the multifunctional robotic arm(s) is attached to the UAV, the main flying system, via the soft link. The uneven or changing forces and loads applied on the aerial robot during aerial manipulations need to be carefully considered when developing dynamic models of aerial robots.

This study presents innovative development of an aerial robot, called the Dexterous Aerial robotic System (DFTS), that has a flexible robotic manipulator, called the vertical take-off and landing platform (VTOL) which is pivotally attached to the UAV via the soft link; and it can be therefore considered as an active 6-DOF soft-link flying platform. The VTOL is equipped with a controllable multifunctional gripper.

The rest of the paper is organized as follows. Section II presents materials and methods with the detailed descriptions of the proposed DFTS, as well as the dynamics and control issues. Section III presents the experimental demonstrations and results. Finally, Section IV presents the summaries, brief discussions, conclusions and further studies.

II. MATERIALS AND METHODS

A. *A design concept of the Dexterous Aerial Robotic System*

The proposed DFTS is described as shown in Fig.1, in which the active flying platform VTOL with the controllable multifunctional gripper is connected to the main flying system UAV via a soft link. The lifting force is provided by VTOL, the additional flying platform, which has a smaller mass and the size. Figure 1(c) describes the functional units of the active flying platform VTOL, including the following key elements: a support arm, a universal joint, a self-stabilized gripper, motors, propellers with motors and Electronic Speed Controllers (ECS), and a control unit.

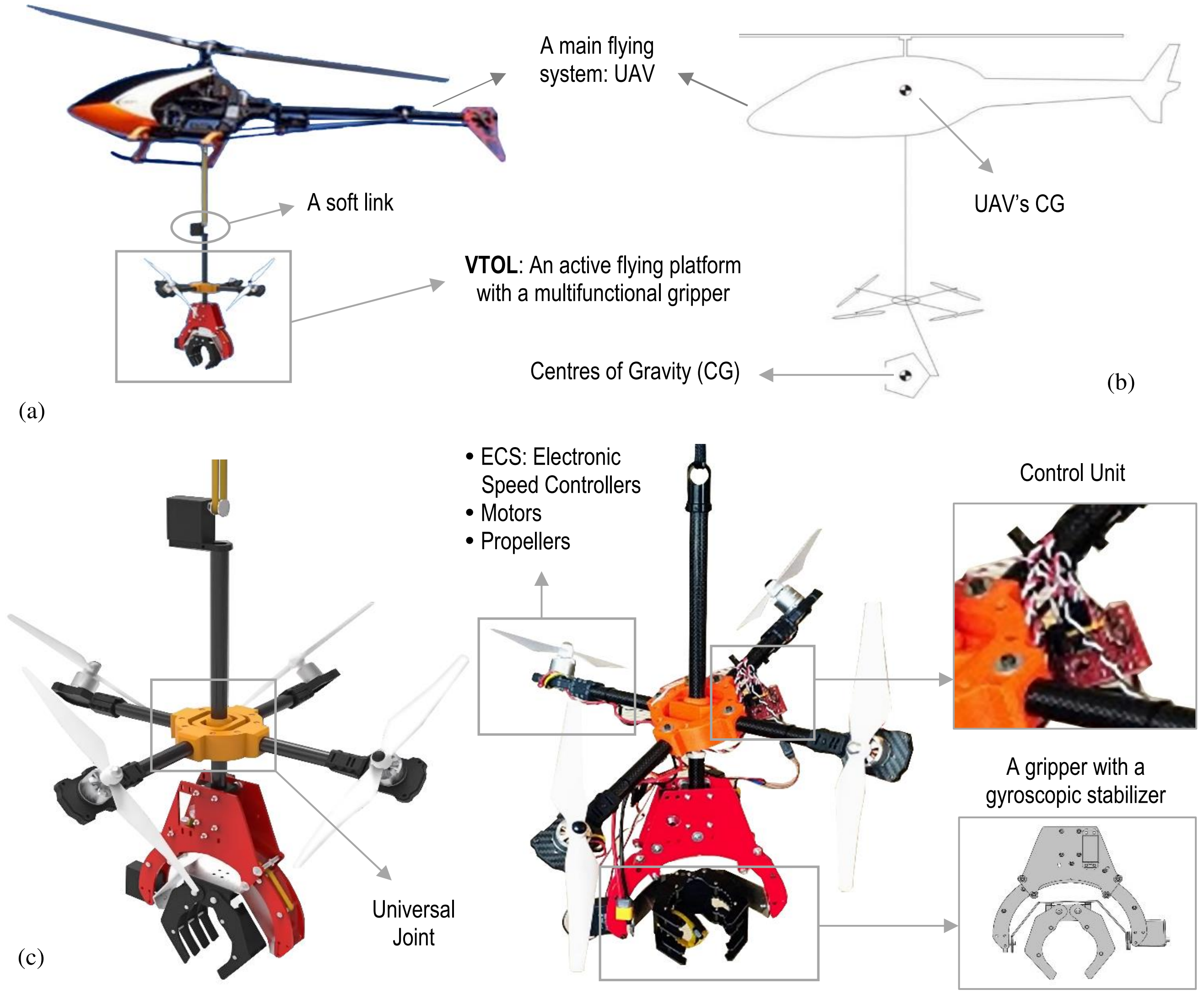

Fig.1. (a): A proposed DFTS include the active flying platform VTOL with the controllable multifunctional gripper connected to the main flying system UAV via a soft link. (b): Centers of gravity (CG). (c): Functional units of the active flying platform VTOL.

The DFTS is designed with the main functions of positioning and stabilizing the objects in space with a minimal impact from the dynamic forces and loads during the aerial manipulations. It also means that, the main centers of gravity of the whole DFTS system including the UAV and VTOL, should remain unchanged, or optimally controlled with a minimal impact from the dynamic forces and loads as well as other related variants. It is important to note that the control of the UAV influences the control of the VTOL, and their centers of gravity need to be always located in one vertical axis as described in Fig.1 (b)).

The support structure of the VTOL is a circular carbon tube, in which a multifunctional gripper is fixed to one end, and the other end is the soft link attached to the UAV. The support structure is designed with additional functions of carrying the power supply battery pack and cables.

Figure 2 presents the 3D design of a universal joint which is one of the key elements of the VTOL. To make it convenient for developing the proof-of-concept prototype, the universal joint shown in Fig.1 (c) is a modified base of the UAV. The universal joint can provide the inclinations on the X and Y axes (Figs. 2), with the rotations of being up to +/- 40 degrees.

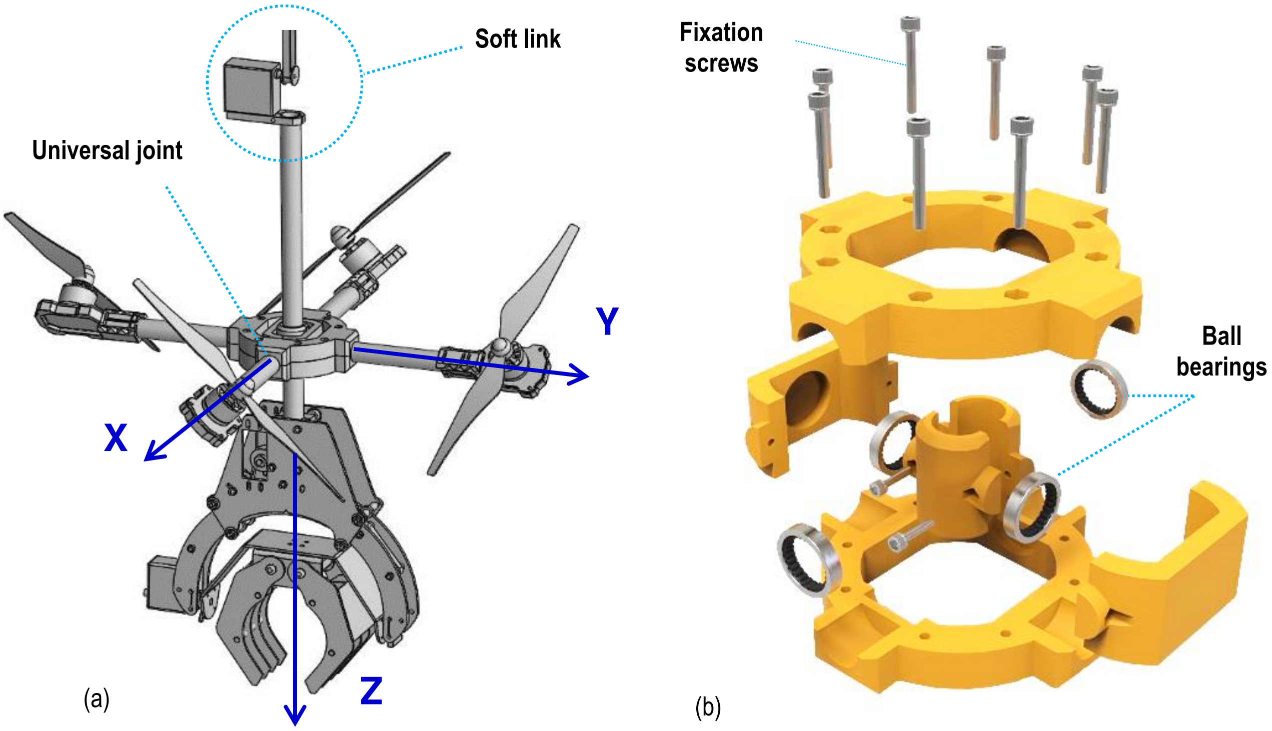

Fig.2. (a): The VTOL with the controllable multifunctional gripper which is connected to the UAV via a soft link. (b): The exploded view with the key parts of the universal joint.

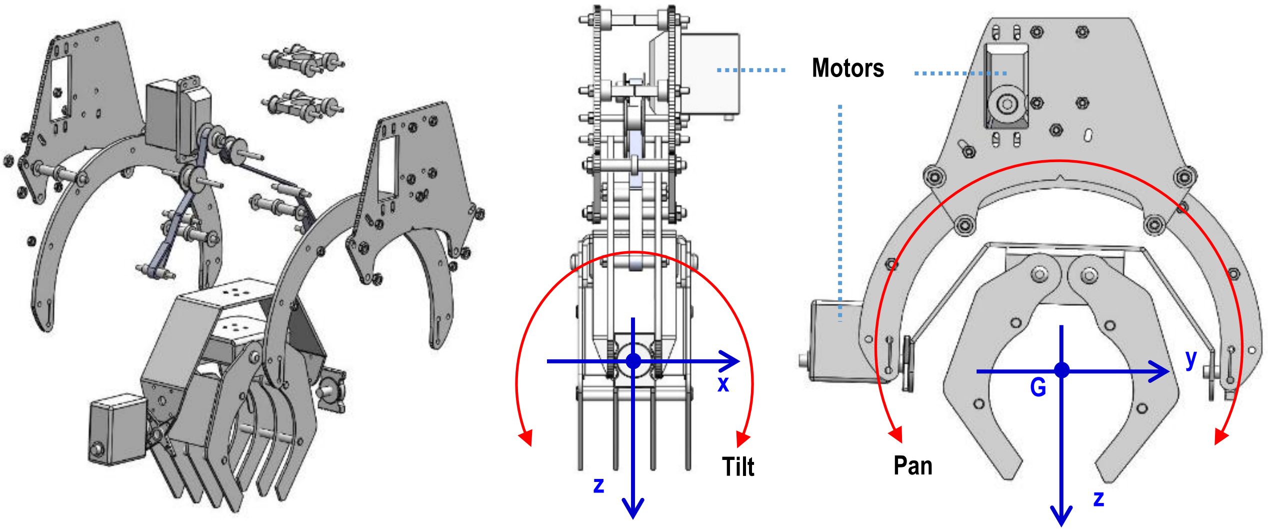

Fig.3. A 3D design and an exploded view of a gripper with two jaws, in which the pan and tilt rotations around x and y axes of the local coordinate system G are operated by servo motors.

Figure 3 presents a 3D design and an exploded view of a gripper with two jaws, which are operated by servo motors. When moving in space, the position of a gripper which is relative to the earth's coordinate system is not fixed. Therefore, the continuous positioning of a gripper is required, and this is accomplished by using a gyroscopic stabilizer, a gyroscopically self-stabilizing unit, which is made of composite materials and metals, and the rotations around x-axis (pan rotation) and y-axis (tilt rotation) of the local coordinate system G (Fig. 3) are operated by servo motors.

The propulsion unit of the active flying platform VTOL include the following elements: four motors, four propellers and one ECS (Electronic Speed Controller). The positioning and movement of the propellers and rotors are done with the following order, based on the main coordinate system XYZ as shown in Figs 3 and 5: (a) Rotor # 1 rotates in the positive direction to the Z axis; it is parallel to the XY plane, and at an angle of -45 degrees to the X axis; (b) Rotor # 2 rotates in the negative direction to the Z axis; it is parallel to the XY plane, and at an angle of -135 degrees to the X axis; (c) Rotor # 3 rotates in the same direction as Rotor # 1; it is parallel to the XY plane, and at an angle of 135 degrees to the X axis; and (d) Rotor # 4 rotates in the same direction as Rotor # 2; it is parallel to the XY plane, and at an angle of 45 degrees to the X axis.

B. Dynamics & Control of the Dexterous Aerial Robotic System

1. Weight and inertial forces

The dynamic behaviour of the proposed the aerial robot DFTS, consisting of the UAV with one or more robotic arms, is closely dependent on the inertial moments and the weight of the elements of the DFTS. This means that the moment of inertia changes significantly and the overall centre of gravity changes constantly, leading to the reaction forces and movements that cause instability of the aerial robot, especially the active flying platform VTOL.

$$M_a(q)\ddot{q} + C_a(q,\dot{q})\dot{q} + G_a(q) = \tau$$

Where M is inertial moment matrix, C is the centrifugal force, g is the vector of gravity.

$$q = [q_y\, q_1^T\, q_2^T\, q_m^T]^T$$

The input signal τ can be represented as:

$$\tau = [\tau_y\, \tau_1^T\, \tau_2^T\, \tau_m^T]^T$$

Where $q = [q_1\, q_2 \ldots q_M]\, T$ are the angles of deflection of the joints and $M_a \in R^{MxM}$, $C_a \in R^M$ и $G_a \in R^M$ are the values of weight, Coriolis and gravitational forces, respectively. The vector $\tau \in R^M$ is the thrust applied by the motors of each joint.

It is assumed that the whole system works as one. Then we can consider the forces as the sum of the constant inertial moment matrix I_b of the UAV, and the variable inertial moment matrix I_a of the gripper:

$$I_{total} = I_b + I_a$$

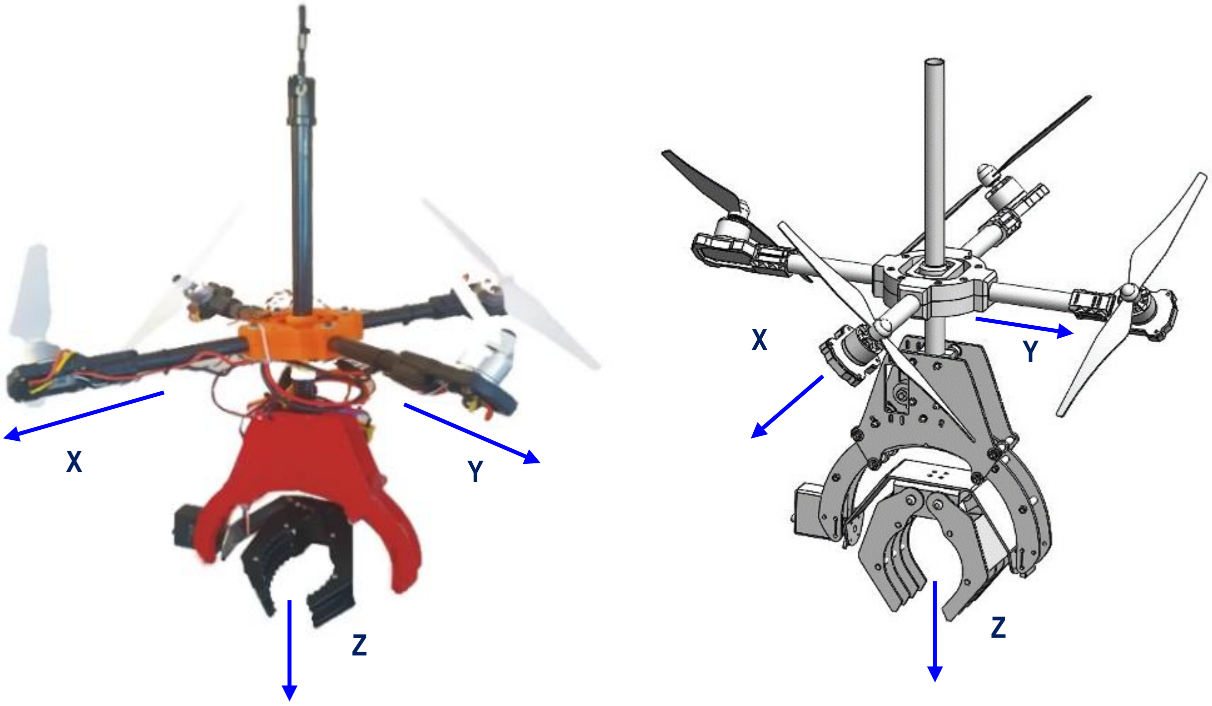

Fig.4. A coordinate system of the active flying platform VTOL with the origin of the coordinate system is centered at CG of the VTOL.

The equations of the dynamic model of the robotic arm with M joints can be derived from the Denavit-Hartenberg formalism; and they can be expressed in a compact matrix form. With the proposed design of the DFTS as described in Section II (A), the lifting force is absorbed by the main flying system (UAV), the active flying platform VTOL can be considered as a flying system with the horizontal orientation only. In this way, mathematically, we have the following equation:

It is clearly seen that, the position of the centers of gravity changes, and it depends on the position of the gripper in particular, and the positions of the active flying platform VTOL in general.

2. The coordinate system of the UAV

For convenient computations, the coordinate system of the active flying platform VTOL is shown in Fig.4; the origin of the coordinate system is centered at the center of gravity of the VTOL.

The axis X starts from the center of gravity (CG) and towards the nose of the UAV. The axis Y starts from the center of gravity and to the right of the UAV. The axis Z starts from the center of gravity and downwards from the VTOL following the right-hand rule.

III. SIMULATIONS, DEMONSTRATIONS AND RESULTS

The proof-of-concept prototypes of the DFTS in general and the VTOL in particular were virtually and physically developed and tested. The simulations and experiments were implemented, with the focus on the following objectives: (i) To determine the working envelope of the DFTS at different soft link lengths, (ii) To determine the time to reach the service zone when deviating from the Z axis with and without the load; and (iii) To determine the stability of the system when it is operated with a 360-degree rotation of the active flying platform VTOL.

The dynamics of the VTOL and the control of a gyroscopically self-stabilizing unit are simulated with the use of Simulink® (The MathWorks, Inc: www.mathworks.com). To make it convenient for the experiments, the VTOL is operated in the manual mode.

It is noted that, the inclination angle is dependent on the length of the soft link (Fig.1 (a)). The experiments were done to determine the working envelope of the DFTS at different soft link lengths at different soft link lengths, in which the system remains stable. The active flying platform VTOL was practically mounted to a fixed tripod, to ensure the free oscillatory motion of the VTOL in the horizontal plane. The experimental results showed that, the active flying platform VTOL can self-stabilize with the inclination angle of being up to 8 degrees, as shown in Fig. 5.

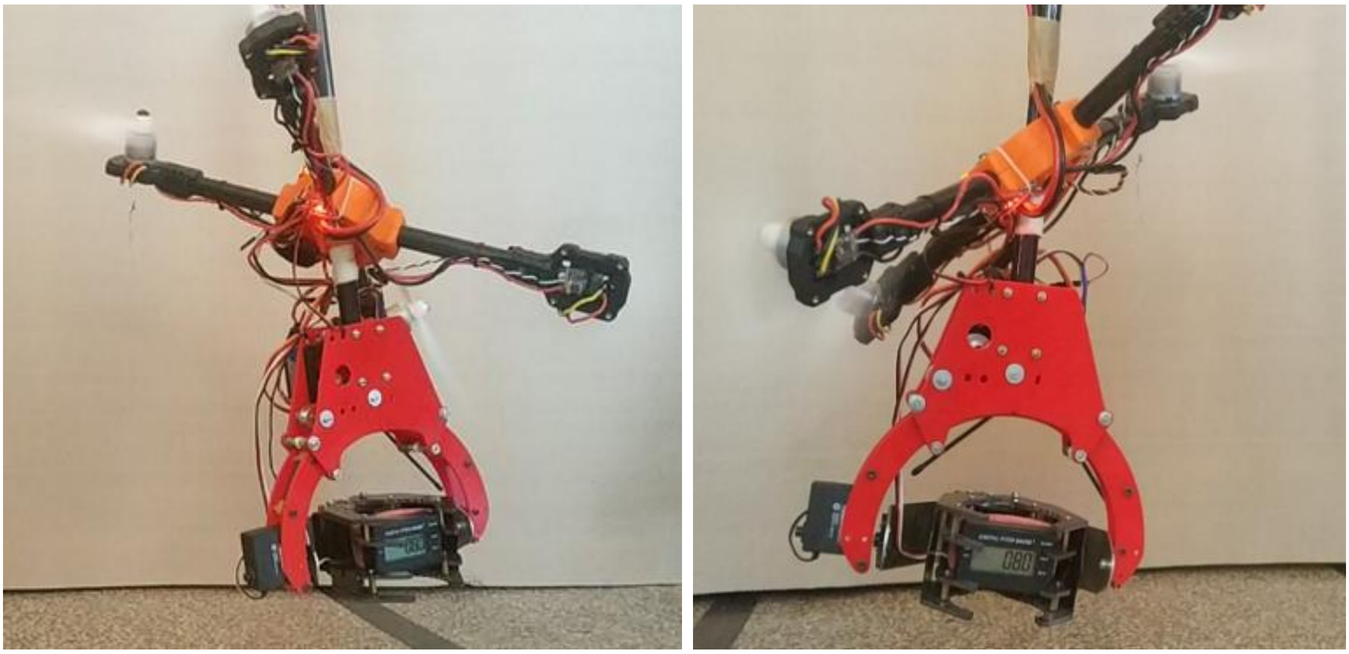

Fig.5. The demonstration of the experiments in which the active flying platform VTOL can self-stabilize with the inclination angle of being up to 8 degrees.

IV. SUMMARY, DISCUSSIONS AND CONCLUSIONS

It has been well-recognized that the potential applications of aerial robots in industries are huge, including the use of aerial robots in warehousing and manufacturing operations as well as inspections, rescue operations, monitoring and surveillance [3-5, 7-9]. Currently, most of the aerial robots are manually operated and controlled, and there is a growing interest of developing autonomous aerial robots in recent years.

Depending on the specific applications and technical requirements of interacting with objects, the aerial robots can be classified with two main interaction types: the direct interaction and the indirect interaction. The aerial robots with the direct interactions are the robotic systems that are equipped the specific mechanism for a specific type of aerial manipulations, such as the aerial robots which were developed in the European Commission funded project, AEROARMS [9]. There are limitations and challenges when developing aerial robots with the direct interactions. Firstly, there are dynamic dependencies that limit the maximum payload of the aerial robot and the weight of the object that is manipulated by the aerial robot. Secondly, there are the problems caused by the turbulent airflows. Finally, there are the risks of colliding with the rotating elements of the UAV.

To minimize or avoid the above-mentioned weak points of the aerial robots with the direct interactions, there has been a growing interest of developing aerial robots with the indirect interactions, in which an object is remotely or indirectly manipulated with the use of robotic arm(s) or arial manipulation unit(s), which are attached to the UAV via a long flexible or soft link. Such connection solutions via the flexible or soft links make it possible to perform aerial manipulation missions; and it is especially effective and safe, when manipulating objects in difficult and in accessible environments.

In this paper, an innovative development of an aerial robot DFTS, was proposed to indirectly manipulate objects in space. The newly proposed DFTS consists of two independent but interconnected systems or functional units, which have two main separate functions respectively, including (i) a basic carrying function which is actually the main flying system, the unmanned aerial vehicle (UAV), remotely controlled and piloted, and (ii) a precise positioning and stabilization function which is the active flying platform VTOL with 6-DOF arial manipulations, and it is attached to the UAV via the soft link. With the use of a long soft link for the aerial robot with 6-DOF arial manipulations, the problems which are caused by the air turbulent flows generated by the UAV are minimized, and the aerial manipulations of objects are safely controlled and effectively operated. The VTOL which is equipped with a grasping mechanism was successfully developed, prototyped and tested. The experimental results showed that, the developed VTOL can self-stabilize with the inclination angle of being up to 8 degrees.

The outcomes from this study will be used as the foundation to fully develop the aerial robots for the specific applications in industries, with the focus on the following: inspections and reparations of various structures such as wind turbines, power lines and open gas pipelines, decorations and painting of high industrial chimneys and walls of high buildings, transport and delivery of courier shipments, relocation and manipulation of assemblies and units in inaccessible or dangerous environments, warehousing and manufacturing operations in smart factories.

The key challenges and difficulties that need to be solved as well as the future implementations of a study can be summarized as follows: (i) Robust and optimal control of aerial robots with indirect interactions, in which its centers of gravity remains unchanged, and the dynamic impacts from the resultant forces and loads are minimized during the aerial manipulations; (ii) Development of optimal dynamic models of aerial robots when uneven or changing forces and loads are applied on the aerial robot during aerial manipulations; (iii) Simulations and optimizations to enhance the performance of aerial robots, taking into account the issues related to stabilizations during the aerial manipulations, enhancement of mechanical strengths, and energy saving via topology optimization, sustainable design and manufacturing principles; and (iv) Integration with smart systems and collaborative robots for applications in Smart Manufacturing and Industry 4.0.

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