Aerospace Science and Technology 39 (2014) 596–604

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Autonomous formation flight of multiple flapping-wing flying vehicles using motion capture system

Ho-Young Kim, Jun-Seong Lee, Han-Lim Choi, Jae-Hung Han *

Department of Aerospace Engineering, Korea Advanced Institute of Science and Technology (KAIST), 291 Daehak-ro, Yuseong-gu, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form 5 June 2014
Accepted 4 July 2014
Available online 12 July 2014

Keywords:
Flapping-wing flying vehicles
Formation flight
Path-following control
Motion capture system

ABSTRACT

This study demonstrates an autonomous formation flight of multiple flapping-wing flying vehicles for the first time. In order to extract the position and attitude information of each flying vehicle, an external motion capture system is applied. A path-following controller is designed so that each flapping-wing flying vehicle has a time-independent circular path with the predetermined radius, and the constant forward flight speed and altitude. Due to the variations in flight characteristics among four different flapping-wing flying vehicles, the gain of the directional control, which generates nonlinear rolling moment using the changes of the tension in flexible membrane wings, is individually tuned for each vehicle. The rotational speed of the circular path is kept constant by controlling the desired radius rather than the forward flight speed so that the formation angles between two closest flapping-wing flying vehicles are maintained at 90 degrees. The performances of the individual path-following controllers and the circular formation controller are statistically evaluated in terms of the mean and standard deviation of the flight state variables.

1. Introduction

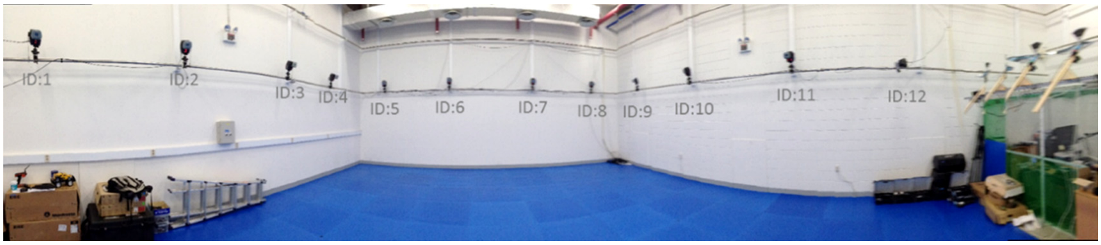
The wing motions and morphologies of nature's flyers have been optimized through a long-term evolutionary process in order to obtain controlled and stable flights. To understand the flight principles of these efficient and stable flapping-wing flights, many researchers have studied the aerodynamics and flight mechanics of insects, birds, and bats [3,11,19,25]. Numerous efforts have also been made to mimic or imitate the wing motions and morphologies of nature's flyers toward the development of flapping-wing flying vehicles with robust and agile flight characteristics [1,5,10,12,13,15,20]. In contrast to biological flyers' diverse wing motions, most of man-made flapping-wing vehicles have less degrees of freedom, which results in unsatisfactory flight control capability. Many successfully developed flapping-wing vehicles even have only one degree of freedom for their main wing motion; the additional tail wing motion provides control effects for those kinds of flapping vehicles [7,17,18]. The capabilities of onboard sensors, actuators, and flight control systems are also seriously limited due to the small payload capacities of flapping platforms. On the other hand, the flight dynamics characteristics of flapping vehicles are often much more complex than the conventional fixed-wing or rotary type air vehicles; a complex limit cycle behavior for the trim or an inherent instability is often observed [7,18]. Complex flight dynamics and "light" flight control hardware make these under-actuated systems very difficult to be autonomous; there have been reported relatively small number of studies on flight controls or autonomous flights of flapping-wing air vehicles.

AeroVironment is one of the pioneers in the development of the flapping-wing flying vehicles [24]. Nano hummingbird is a tailless insect-like flapping-wing flying vehicle, which does not have internal stability for a hovering flight [13]. However, this piece of cutting-edge technology is also under an extreme weight budget constraint. To meet the tight weight budget and mission requirements such as flight endurance and video transmission, no accelerometers nor global-positioning-system (GPS) receiver were used. Only a 3-axis gyro and a low performance microcontroller for control system in addition to a skillful pilot's command via a radio control were used for the flight stabilization [12,13]. Krashanitsa et al. [15] developed a 74-cm-wing-span ornithopter equipped with an automatic flight control system that provides stability augmentation and navigation of the vehicle as well as flight data acquisition. The flapping vehicle demonstrated successful waypoint and altitude navigation during the autonomous flight. Recently, Hsiao et al. [10] performed the altitude control of 10 gram class flapping-wing micro-aerial vehicles with a non-intrusive navigation methodology by using stereo vision. They reported that the

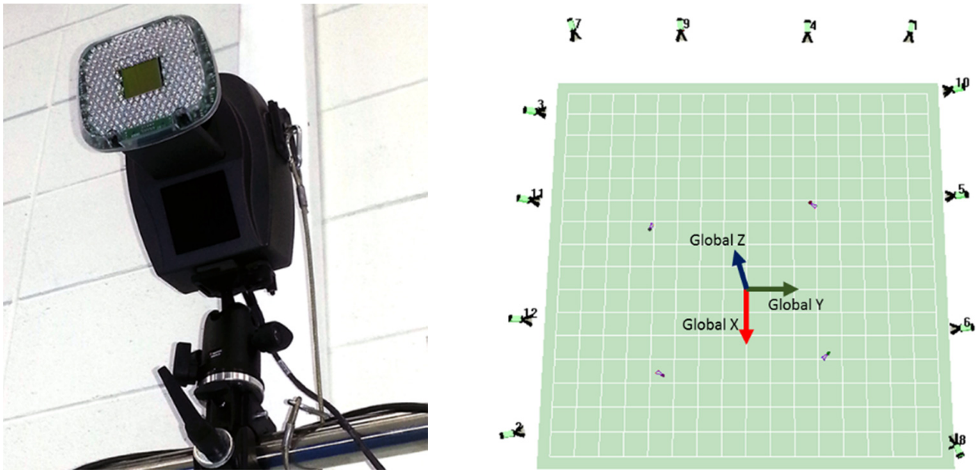
---

* Corresponding author. Tel.: +82 42 350 3723.
E-mail address: jaehunghan@kaist.ac.kr (J.-H. Han).

http://dx.doi.org/10.1016/j.ast.2014.07.004
1270-9638/



(a) KAIST Arena with real-time positioning environment



(b) Motion capture camera

(c) Ground station view

Fig. 1. Motion capture system in KARPE.

selections in control methods were limited due to the restrictions in carry-on weight. Researchers at Delft Technical University have poured their efforts toward the autonomous flight of their famous flapping-wing platform, Delfly II [1,5]. Recently, they developed a low-cost high performance control system to enable autonomous untethered flight inside a wind tunnel [5]. Off-board infrared tracking sensors were used to extract position and attitude information of the vehicle, and 1.5 g onboard autopilot containing inertial measurements were used to autonomous untethered flight. The same group used the same external tracking system to perform controlled flight test maneuvers for the system identification purposes.

In order to utilize the small-sized flapping-wing flying vehicles for practical intelligent, surveillance, and reconnaissance missions (ISR), the problem of insufficient payload capability needs to be overcome [8]. One of the promising solutions is the coordinated operation of the multiple flight vehicles, which allows the distribution of ISR sensors onto a number of small aerial vehicles [2]. This operation can distribute the mission payloads to several vehicles so that they can share the mission functionalities to overcome limited payload affordability of each single vehicle. Formation flight and cooperative mission accomplishment have been intensively investigated for the multiple rotary-wing flying vehicles [16,21]; however, the similar study using multiple flapping-wing flying aerial vehicles has not been reported yet.

This paper presents an autonomous formation flight-test result of multiple flapping-wing flying vehicles for the first time. A commercially available, small-sized flapping-wing flying platform is modified for this purpose. The payload margin of the flying vehicle is very small to implement additional on-board sensors and actuators for constructing the feedback control loops. The motion capture system, which has the same function of the global positioning system in indoor environment and requires no less than three reflective markers on the subject, is employed as a sensor system [9,20,23]. With little added weights, all of the state variables of the flight vehicle can be obtained in almost real-time so that they can be used in the closed-loop flight control. To preserve the intrinsic stability of flapping-wing flying vehicles, all of the control inputs are generated in a cycle-averaged manner. The sophisticated wing membrane structure results in significant variations in aerodynamic and flight dynamic characteristics for different vehicles, demanding the control gain tunings for each vehicle. Time-independent circular path with the pre-determined radius and the altitude is chosen as the desired trajectory of the flapping-wing flying vehicles, and the flight vehicle follows the trajectory using a path-following controller. The performances of the individual path-following controllers and the circular formation controller are statistically evaluated in terms of the mean and standard deviation of the flight state variables.

2. Experimental setup

2.1. Motion capture system

A motion capture system is an external sensor system, which provides three-dimensional position of the tracking targets in almost real-time with the minimum time-delays. KAIST Arena with Real-Time Positioning Environment (KARPE) is an indoor flight test-bed using the motion capture system (Fig. 1(a), *Motion Analysis Corp.*) which consists of the 12 IR strobe cameras (Fig. 1(b)) placed in the volume of 8.9 m × 12.3 m × 5 m (Fig. 1(c)). Each camera has 1.3 million pixels of the resolution and the maximum frame rate and shutter speed are 500 fps @ 1280×1024 pixels and 30 kHz, respectively. The spatial measurement uncertainties in the horizontal (X–Y) and the vertical (Z) directions are 0.145 mm and 0.187 mm, respectively, in the root-mean squared sense [14].

2.2. Flapping-wing flying vehicles and launching device

A sufficient turning rate of the flapping-wing flying aerial vehicle is required to conduct the flight-testing in the confined area so that the vehicle can avoid the collision with other vehicles and wall. A commercial flapping-wing flying vehicle, *Avitron* (*XTIM*),