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Systems design and implementation with jerk-optimized trajectory generation for UAV calligraphy

Swee King Phang [a,*], Shupeng Lai [a], Fei Wang [b], Menglu Lan [c], Ben M. Chen [c]

[a] NUS Graduate School for Integrative Sciences & Engineering, National University of Singapore, 21 Lower Kent Ridge Rd, 119077 Singapore, Singapore
[b] Temasek Laboratories, National University of Singapore, 21 Lower Kent Ridge Rd, 119077 Singapore, Singapore
[c] Department of Electrical & Computer Engineering, National University of Singapore, 21 Lower Kent Ridge Rd, 119077 Singapore, Singapore

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ABSTRACT

Unmanned aerial vehicle (UAV) and Chinese calligraphy seem like two completely unrelated subjects in today's world. UAV, as one of the most advanced technology to date, has gathered much attention lately due to its potentially unlimited applications. Contrarily, Chinese calligraphy is one of the most beautiful and ancient calligraphy art originally developed from China few thousand years ago. Today in this manuscript, we present to you the art of autonomous calligraphy writing with UAVs. The proposed UAV calligraphy system is able to trace the user handwritten inputs, and then execute the writing by mimicking the user handwriting with four autonomous UAVs. This manuscript details the design considerations and implementation process of such a system. The UAV calligraphy system was performed in Singapore Airshow 2014. Robustness and reliability of the system has been well tested, and high performance can be seen from the resulting calligraphy writing.

1. Introduction

Driven by the advancement in processing power of tiny micro-processor, the unmanned aerial vehicle (UAV) research has reached a new horizon where they are getting smaller in size but smarter. Many researchers have shifted their attention from the usual UAV to small scale or miniature UAV development [20,21,24]. Due to their small size and light weight, these UAVs are capable of maneuvering indoors for the various missions or tasks. In particular, UAVs of quadrotor platforms are most frequently used by the researchers, due to their simplicity in structure and scalability. In general, a strong micro-processor and an inertial measurement unit (IMU) are needed for orientation control of a quadrotor, while GPS localization is used for outdoor position control. In the environment where GPS signal is not available, e.g. indoor environment, a different localization method will be needed. Visual based navigation was introduced in [9,11,12] to estimate the relative distance of the UAV from its original position, while the researchers from the University of Pennsylvania were one of the first few group to utilize the Vicon motion tracking system to measure the UAV in a confined space [23]. Once the localization issue of the indoor UAV is solved, control and navigation problem such as trajectory generation can be handled [6,7,13,14,17,22,39,40].

Chinese calligraphy is one of the finest of all Chinese traditional arts. It is an inseparable part of Chinese history, and its delicate aesthetic appreciation are commonly considered to be unique among all calligraphic arts [34]. In this manuscript, we proposed to combine this traditional Chinese art together with the modern development of UAV, to perform what we called UAV calligraphy (see Fig. 1). Prior to our development, many researchers have investigated the generation of strokes of Chinese characters in simulation [32,35,38]. In the work documented in [33], the authors visually analyzed and then classified the Chinese calligraphy characters. To the best of our knowledge, there are, however, no research or successful example of calligraphy writing with any aircraft or flying machine. The closest example sees the development of an omnidirectional ground vehicle to perform calligraphy writing [10], while most of the development in automated calligraphy writing was realized with robotic arms [5,18,19,31,37].

We have identified a few challenges in realizing autonomous UAV calligraphy writing. In most of the applications documented in the literature, 6 degree-of-freedom (DOF) robotic arm is used to execute the writing. They are able to trace simple B-spline optimized trajectories [36]. In our work, we need to incorporate the UAV's dynamics in path generating and thus it increases computational complexity and loads to the calligraphy writing system. As

* Corresponding author. Tel.: +65 97789556.
E-mail addresses: king@u.nus.edu (S.K. Phang), shupenglai@u.nus.edu (S. Lai), tslwf@nus.edu.sg (F. Wang), lanmenglu@u.nus.edu (M. Lan), bmchen@nus.edu.sg (B.M. Chen).

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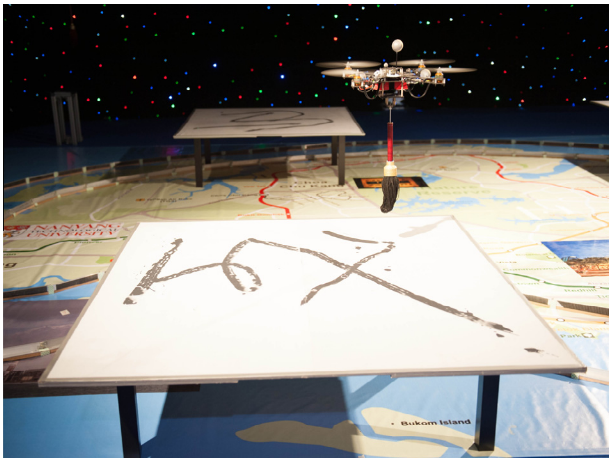

Fig. 1. UAV calligraphy performance in Singapore Airshow.

the airborne UAV must always remain upright, we thus consider only 3 translational DOF in executing the calligraphy writing. As we wish the calligraphy writing system works on the handwriting of user input, the second challenge occurs in decoding of user handwriting to the information recognized by the machine. Besides a simple graphical interface for user handwritten input (see Fig. 2), a sophisticated algorithm is needed to extract important turning points of the handwritten character. Lastly, the mechanical design of the calligraphy brush and its connector to the UAV poses an important challenge to us. Unlike the robotic arm, the force applying to the calligraphy brush during writing will be reflected back to the airborne UAV, and thus affects its stability. A sophisticated UAV control scheme needs to be revised, together with a creative design of the calligraphy brush to make the system work with as little disturbance as possible.

The implemented UAV calligraphy system is first introduced to the public in Singapore Airshow 2014 [27]. Singapore Airshow is one of the world's largest aviation event held biyearly in Singapore. It has attracted exhibitors from more than 50 countries to participate and to showcase their development in aviation sector. Our team from the National University of Singapore, has realized four UAVs writing four different Chinese characters simultaneously. The handwriting tracing system is also proven to work well as the public handwritten input is sketched by the UAVs on the spot.

This manuscript documents the design architecture and the implementation procedure of the UAV calligraphy system. Section 2 details the design and implementation of the hardware needed to realized UAV calligraphy. Controls and implementation on the UAV will be discussed in Section 3. Sections 4 and 5 shows the handwritten character strokes tracing and trajectory generating, which makes the core content of this manuscript. Results of the UAV writing calligraphy will be shown in Section 6, while Section 7 gives concluding remarks of our work.

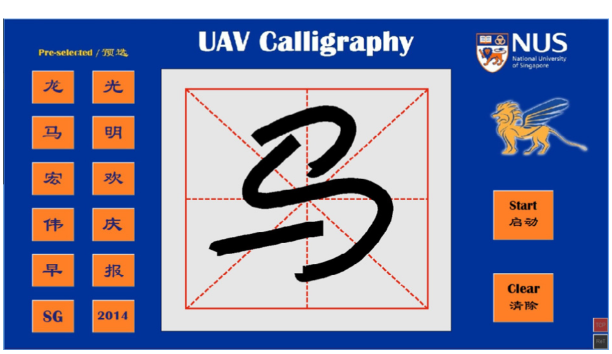

Fig. 2. Graphical interface for user handwriting input.

2. Hardware setup

The UAV calligraphy system is able to work on any miniature self-stabilized UAV in general. In our project realization, quadrotor UAVs with high orientation control bandwidth are utilized. Each quadrotor has four propellers of 10 inches in diameter and has the largest dimension of 40 cm from motor to motor. It is approximately 1 kg and has a high inner-loop bandwidth of 25 rad/s. The high bandwidth enables a fast tracking outer-loop controller to be designed, as will be shown in Section 3 later.

To realize calligraphy writing, a calligraphy brush together with the holding mechanism is customized. The full overview design of the brush can be visualized in Fig. 3. More specifically, we wish to highlight an important design consideration to realize UAV calligraphy – the linear bearing joint (zoomed view in Fig. 3). A linear bearing is included at the base of the brush holder, while a shaft attached to the brush passes through and is locked to the bearing. The installation of such a mechanism enables the following two points.

1. A free low-friction linear movement along z-direction of the brush with reference to the UAV above it. This reduces the disturbance to the airborne UAV resulted from the contact between the calligraphy brush and the writing board. Performance of the UAV will thus not be affected during the contact-writing instances.
2. The calligraphy brush can be rotated freely along z-axis, resulting smooth and natural writing along an arc or circular drawing.

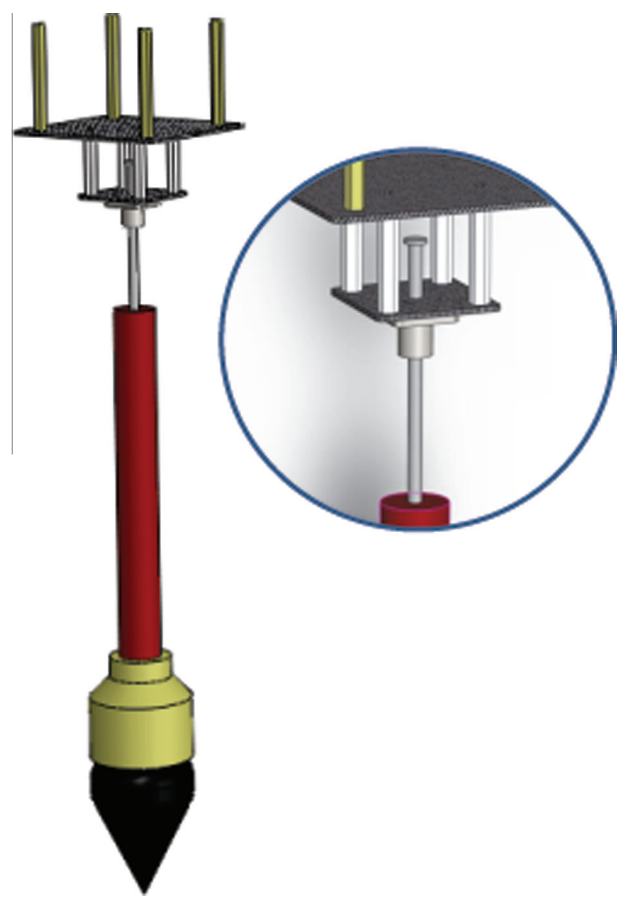

Fig. 3. The designed calligraphy brush and its holder.