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論　文

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進化を続けるジャーナル

テクニカルジャーナル編集委員長
一般社団法人日本 UAS 産業振興協議会
常務理事　岩田　拡也

2025 年がスタート致しました。謹んで新年のご挨拶を申し上げます。

一般社団法人日本 UAS 産業振興協議会（JUIDA）が発行するテクニカルジャーナルは，ドローン産業の振興に役立つ技術情報を産業界の皆様に提供するために創設されたオンライン技術情報誌で，掲載論文は年々増加を続けておりますとともに，ジャーナル自体も進化を続けております。例えば，昨年 2024 年は，技術情報の速報性を向上するため Letter 制度を新設致しました。その結果，大学等の研究室からの速報性の高い論文の投稿が増加致しました。Japan Drone 展でのポスターセッションに大学の研究室から出展し，大学院に進んで論文にまとめ本誌に投稿頂いた例もございました。また，ベンチャーや中小企業の皆様からも論文を投稿頂き，採録となった開発成果をポスターセッションで発表頂いたことで，様々な企業様との連携や商談に繋がった例は，まさに本誌の目指す姿の一つでございます。

今年の Japan Drone2025 でも，本誌のポスターセッションを開催致します。企業やスタートアップの皆様には，実証実験や製品開発，サービスやソリューション創出などで得た先進的な取り組みや知見をご発表いただき，商談に結実する機会として，また日本のみならず世界へ発信する広告としてお役立て頂ければ幸いです。もちろん，大学研究室の若き学生の皆様にも，査読付きの論文となりますので奮ってご参加頂き，研究者としての登竜門として頂ければと存じます。

昨年年始の能登半島の大震災で焼けた街並みと，ウクライナや中東の戦争で焼けた街並みは，よく似ているようで人の絆を伴うか人の憎悪を伴うかの点で対局にありますが，どちらもドローンの活用が促進している点に私達の未来への責任を感じます。JUIDA では，人の絆を伴う前者の災害支援とドローンの関係強化に向けて最大限の取り組みを行っているところです。本誌も，防災とドローンを組み合わせた特集号等を企画することにより，ドローンの技術情報を社会に役立てることができないか模索していきたいと考えております。

ドローンをこのように活用したら現場で役立った，ドローンと何かを組み合わせることで問題を解決できたといった技術情報や実例が多く投稿され，様々な方面に共有されることで本誌も社会や世界に貢献できます。現場で役立ちそうなドローンに関する情報がございましたら，是非奮ってご投稿ください。その一歩一歩の積み重ねが，やがて人々の憎悪の連鎖を断ち切るドローンの活用と，人々の絆を結ぶドローンの活用を生み育てることになると JUIDA は信じます。本年も何卒宜しくお願い申し上げます。

2025 年 1 月吉日

常務理事
岩田　拡也/Kakuya Iwata
産業技術総合研究所 主任研究員。1998 年通商産業省工業技術院電子技術総合研究所に入所。第 16 回電子材料シンポジウム EMS 賞受賞，第 12 回応用物理学会講演奨励賞受賞。白色 LED 開発にてゼロから 1 兆円産業に成長する過程を経験。半導体製造装置開発からロボット技術に目覚め，2004 年に独立行政法人産業技術総合研究所知能システム研究部門に移籍，無人航空機の研究開発をスタート。2007 年日本機械学会交通・物流部門優秀講演表彰を受賞。2008 年に経済産業省製造産業局産業機械課にてロボット政策に従事。2009 年以降「NIIGATA SKY PROJECT」の無人航空機開発を立ち上げる。

Letter

脳波計測によるストレス解析のための実機と CG のドローンにおけるディスクレパンシー評価

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近年，Urban Air Mobility（UAM）に関する技術が世界中で研究されている一方，UAM やドローンの社会受容性については十分に検討されていない。そこで著者らが所属する研究グループでは，アンケートによる主観評価と簡易脳波計測にもとづく感性アナライザによる客観評価を組み合わせた社会受容性評価手法を提案した。この手法の有効性は確認されている。2023 年 12 月に実施された便益効果評価実験では，UAM の社会受容性を向上させる手法として場面想定が提案された。しかしながら，得られたデータの信頼性が不十分であったため，適切な実験環境が設定できていない可能性，および十分な場面想定ができていない可能性があった。また，参加者がいくら場面想定を十分にできたとしても，実際の UAM と CG との乖離は無視し難い。そのため，実験環境を改善することで，実際の UAM と CG のディスクレパンシー（乖離）を小さくする必要がある。本研究では，実際の UAM を用いた実験は困難であるため，ドローン（マルチコプター）を用いてこの種の検討を行う。本発表では，一般の参加者を対象にするのではなく，著者が所属する研究グループの学生を対象に実施された実験について述べる。

Keywords: ディスクレパンシー，脳波計測，感性アナライザ，社会受容性，ストレス，UAM

Discrepancy Evaluation Between Actual and Computer Graphics Drones for Stress Analysis by EEG Measurement

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Technologies related to urban air mobility (UAM) are being studied worldwide. However, the social acceptance of UAMs and drones has not been investigated thoroughly. To address this issue, the authors propose a social acceptance evaluation method that combines subjective assessments by questionnaires with objective evaluations using a Kansei Analyzer based on a simple electroencephalograph. The effectiveness of the proposed method was confirmed. In the benefit-effect assessment conducted in December 2023, scene assumption was proposed as a means of improving social acceptance. However, the reliability of the obtained data was insufficient, and there was a possibility of not preparing an appropriate experimental environment or assuming sufficient scenes. Even if the subject is able to adequately assume the scene, it is difficult to ignore the discrepancy between the actual UAM and CG. Therefore, it is necessary to reduce the discrepancy between the actual UAM and CG by improving the experimental environment. As it is difficult to conduct experiments using an actual UAM, in this study, we used a drone (multicopter) for the investigation. This paper presents the results from a preliminary experiment conducted with students in our research group, rather than with participants from the general public.

Keywords: Discrepancy, EEG measurement, Kansei analyzer, Social acceptance, Stress, Urban air mobility

1. Introduction

Drones are now becoming popular, and industrial drones for logistics and urban air mobility (UAM) for mobile infrastructure are being commercialized. Although there is ongoing research and development on the safety and performance of drones, there has been little research on the social acceptance of the aerial industrial revolution [1]. Social acceptance is generally considered in terms of technical, institutional, and market aspects [2]. However, in this study, it refers to the psychological aspects of the extent of noise and fear accepted by the public. In the past, when new infrastructure was introduced, such social acceptance was not considered seriously. As a result, public protests occurred after airports and high-speed railway lines were built. Although it is necessary to reflect on such experiences, the authors are unaware of any specific evaluation metrics for social acceptance evaluation at present. Therefore, to enable the smooth market introduction of UAM, it is necessary to establish an objective evaluation method for social acceptance, set acceptance criteria, and develop UAM based on such criteria. Hara et al. [3] attempted to objectively evaluate social acceptance by measuring stress levels using an analyzer based on simple electroencephalography.

In addition, according to a psychosocial survey on noise by Yamanouchi et al. [4], it was hypothesized that stress tolerance changes with different applications and stakeholders, even for the same mobility. Furthermore, previous studies reduced the subjective stress measured from drone noise to formulate drone flight operation conditions [5]. However, uniformly setting the noise level and developing drones accordingly cannot necessarily improve social acceptance by citizens or users. Therefore, it is necessary to search for an acceptable noise level for each application and stakeholder. However, such research has not yet been conducted [6]. Takahara et al. [7] conducted a benefit-effect evaluation experiment to clarify the acceptable noise level for each use through the scene assumption method. The results of the experiment showed that the acceptable noise level may be higher when using a UAM with a large social impact compared to daily use vehicles for commuting to work. However, the reliability of the obtained data was insufficient. Therefore, it is necessary to improve the experimental environment and investigate the stress factors. Even if the subject is able to adequately envision the scene, the discrepancy between the real UAM and CG is difficult to ignore. Therefore, it is necessary to reduce the discrepancy between the real UAM and CG by improving the experimental environment. As it is difficult to conduct experiments using a real UAM, in this study, we used a drone for the investigation. We used an analyzer based on simple electroencephalograph (EEG) measurement to evaluate the discrepancy in the stress levels between a real drone and CG drone, and discussed the fundamentals of constructing an experimental environment when using a UAM as a target. In the future, this research aims to contribute to the smooth social implementation of UAM. A preliminary experiment was conducted not with general participants, but with students in the authors' research group. In addition, we summarize the results of a simpler analysis of the preliminary experiment without the weighting described in Section 4-3 in [8].

2. Objective evaluation method using a simple electroencephalograph

Sociopsychological questionnaires are often used to assess emotional changes in social acceptance. However, as these questionnaires are subjective, they cannot accurately capture real-time emotional changes. For the EEG measurement in this study, we employed a Kansei Analyzer (Figs.1 and 2) [9] from Dentsu Science Jam Inc., which is a simple EEG-measuring device designed for emotion measurement. The Kansei Analyzer is a simple electroencephalograph designed to measure five emotional states: stress, concentration, preference, calmness, and interest. Its real-time nature makes it useful for time-series sensitivity assessments. In principle, sensitivity index values are estimated from EEG in real time by pattern matching with a database accumulated over many years such that the feature values based on the EEG shapes and sensitivity index values based on biohormone levels match one-to-one. This is based on the correlation between changes in biohormones related to emotional responses and EEG feature patterns (i.e., hormone fluctuations affect EEG patterns and vice versa).

Fig.1 Kansei analyzer.

Fig.2 Installation method.

3. Stress factors given by drones

To evaluate the stress-level discrepancy between an actual drone and a CG drone, it is necessary to create a CG based on the stress factors imparted by drones to people. In this section, we explain the stress factors that drones cause to people based on related studies. First is the noise, which is considered to be the strongest factor in the stress caused by drones. Unlike other environmental noises (e.g., traffic and aircraft noise), drones generate noise that contains many high-frequency components and pure tones [6]. Owing to this characteristic, drone noise is often perceived as more unpleasant than normal environmental noise. The unpleasantness is amplified by the rapid modulation of sound particularly due to the rotation of the propeller. The second factor is the size of the drone. It has been reported that larger drones have a greater visual presence, and seem more intimidating and dangerous [10]. The third factor is flight altitude. Drones flying at lower altitudes are reported to cause greater concerns regarding noise, safety, and privacy invasion [10]. Finally, the flight speed of the drone is also a factor. Sudden changes in direction and flight at high speeds have been reported to cause stress.

Specifically, at a higher speed, it is more difficult to predict the flight of the drone and there is a greater fear of collision [6]. Based on the aforementioned stress factors caused by drones, we focused on the drone size, which are frequently reported stress factors, and evaluated the stress-level discrepancies between actual drones and CG drones.

4. Experimental method

As a preliminary experiment, we did not involve general participants, but explained the details of the experiment to students (6 students in their 20 s) in our research group, and they consented to cooperate in the experiment.

4-1 Experiment environment and flight path

The actual and CG drones are shown in Figs.3 and 4, and the experimental environment and drone flight paths are shown in Figs.5 and 6, respectively. The drone weighed 249 g, measured 298 × 373 × 101 mm, had a maximum flight time of 30 min, and a noise level of 70 dB at the closest approach (0.8 m from the subject).

Next, the flight path of the drone is described. The drone ascended from a platform 0.4 m above the ground to a height of 1.2 m over a period of 5 s, approached the subject over a period of 15 s, and stopped 0.8 m in front of the subject. The subjects' EEG data for 20 s up to this point were measured using a Kansei analyzer. The CG drone was created based on the size, noise level, and flight path of the actual drone.

Fig.3 Actual drone.

(A) (B)

Fig.4 (A) CG1 drone (Small), (B) CG2 drone (Large).

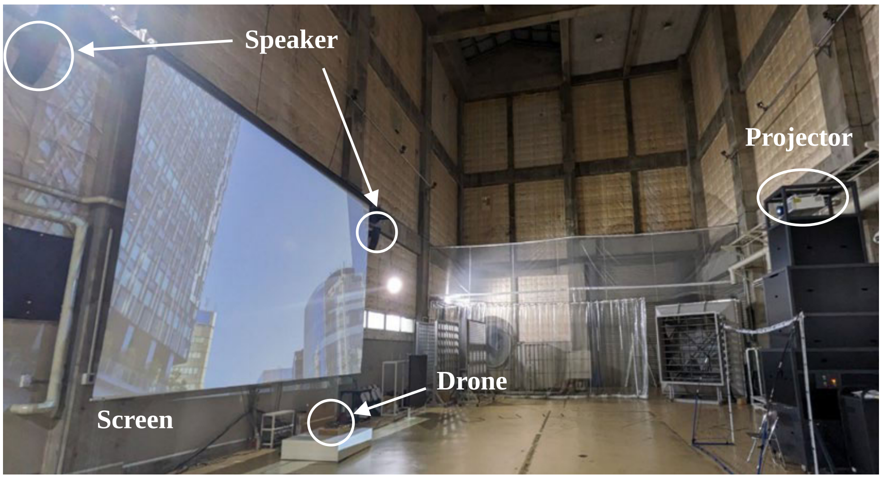

Fig.5 Experiment environment.

4-2 Experimental protocol

The experimental flow is shown in Fig.7. The participants were asked to view three types of drones: an actual drone, a CG1 drone, and a CG2 drone with an interval between them to allow for the questionnaire and rest time. To account for the effect of order, each subject viewed the three types of drones in different orders.

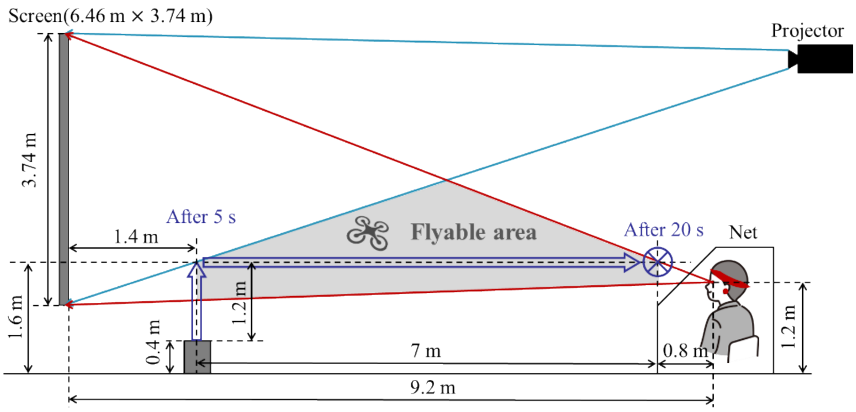

Fig.6　Flight path.

Next, we describe the CG drones. CG1 was a CG-drone that was 2/3 the scale of the real drone, and CG2 was a CG-drone that was 3/2 the scale of the real drone. The CG sounds were recorded from the actual drone flights, processed, and edited. The noise level was measured according to the characteristics of the human ear (characteristic A) [11], which states that human senses become duller for lower loudness and frequency of sound.

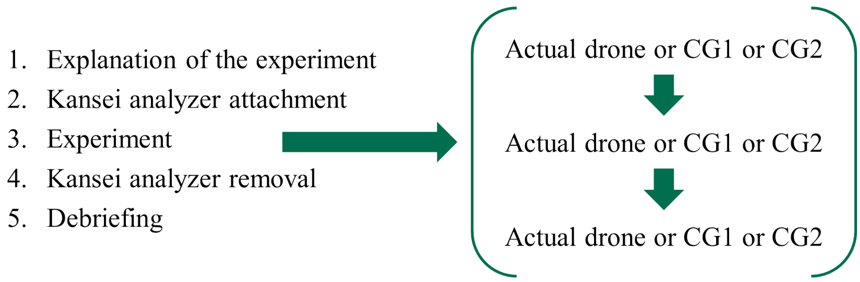

Fig.7　Experimental flow.

4-3　Analysis method

This section describes the analysis method for the stress levels measured using the Kansei analyzer. The discrepancy between the CG drone and real drone was evaluated when the size and noise level of the CG drone were changed. The stress level was measured for 20 s before and after the drone started to fly or when the CG drone started to play its video. The measured data for 20 s before and after the flight were weighted based on the mean and standard deviation of each data point. The data was weighted because it is easier for the stress level to change from 50% to 60% compared to the change from 90% to 100%.

Let us assume a_t as the stress level at time t [s], μ is the mean value, and σ is the standard deviation. Then, the weights w_t are determined according to the following rule.

- $|a_t - \mu| \leq \sigma$, then $w_t = 1$
  - $a_t \to a_t$
- $\sigma < |a_t - \mu| \leq 2\sigma$, then $w_t = 1.5$
  - $a_t \to 1.5a_t$
- $2\sigma \leq |a_t - \mu| < 3\sigma$, then $w_t = 2$
  - $a_t \to 2a_t$
- $3\sigma \leq |a_t - \mu|$, then $w_t = 2.5$
  - $a_t \to 2.5a_t$

Based on the stress level measured by the Kansei analyzer, the weighted average of the stress level of participant i during the 20 s before and after the start of the flight (or the start of the CG) can be expressed using Eqs. (1) and (2), respectively. Let us assume t_s [s] as the time at which the drone flight starts (or CG starts).

$$\bar{a}_{i,1} = \frac{\sum_{t=t_s-20}^{t_s} w_t a_t}{\sum_{t=t_s-20}^{t_s} w_t} \tag{1}$$

$$\bar{a}_{i,2} = \frac{\sum_{t=t_s}^{t_s+20} w_t a_t}{\sum_{t=t_s}^{t_s+20} w_t} \tag{2}$$

Using Eqs. (1) and (2), the stress variation for drone type j for the i-th participant is expressed by Eq. (3). Note that $j = 0$ is the actual drone, $j = 1$ and $j = 2$ represent CG1 and CG2, respectively.

$$x_i^j = \bar{a}_{i,2} - \bar{a}_{i,1} \ (j = 0, 1, 2) \tag{3}$$

Using Eq. (3), the average variation of drone type j for experimental group k is expressed by Eq. (4), where N_k is the number of participants in each experimental group (A or B).

$$y_k^j = \frac{1}{N_k} \sum_{i}^{N_k} x_i^j \ (j = 0, 1, 2, k = A, B) \tag{4}$$

Using Eq. (4), the discrepancy value between the actual drone and CG drone in experimental group k is expressed by Eq. (5).

$$D_k^j = \left| y_k^j - y_k^0 \right| \ (j = 1, 2, k = A, B) \tag{5}$$

In Eq. (5), the drone type with a smaller value is interpreted as having a smaller discrepancy with the real drone. By improving the CG such that D_k^j approaches zero, we can develop a social acceptance simulator to evaluate an appropriate level of stress.

5. Experimental results and discussion

5-1 Experimental results

In this experiment, due to the small number of participants and the focus solely on drone size, only experimental group A is considered. Average stress variation values for all drone types and the distribution of the stress variation shown in **Fig.8** and **Fig.9**, respectively. The deviation values calculated from **Fig.8** are $D_A^1 = 3.18$ and $D_A^2 = 1.04$, indicating that the larger CG drones have smaller deviation values than the smaller CG drones. However, as there is no y_A^0 (actual drone) between y_A^1 (CG1) and y_A^2 (CG2), it is difficult to set the deviation from the actual drone to zero by changing the size of the CG drone. In the distribution of the stress variation for CG1 shown in **Fig.9**, one participant exhibited an unusually high value (16.7%), which significantly influenced the average stress variation value for CG1. According to the questionnaire responses, this participant reported having more frequent interactions with drones in daily life compared to the other participants and indicated feeling no stress toward any of the three drone types viewed during the experiment. Therefore, it is inferred that when viewing CG1, the participant may have experienced heightened stress related to factors other than the drone itself, such as the presence of others or tension in the experimental setting.

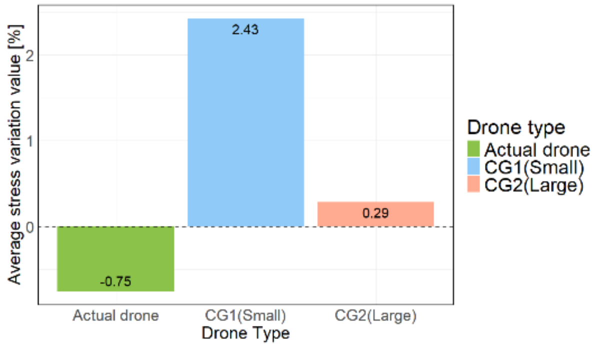

Fig.8　Average stress variation values (N=6).

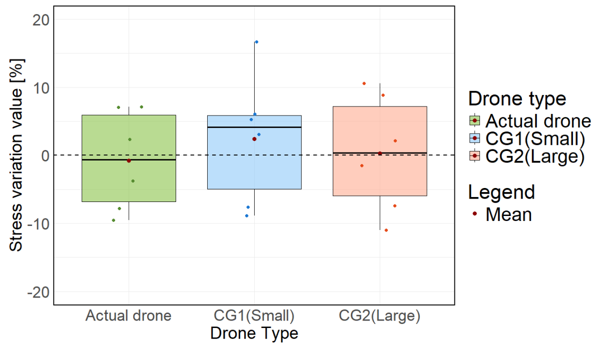

Fig.9　Distribution of the stress variation (N=6).

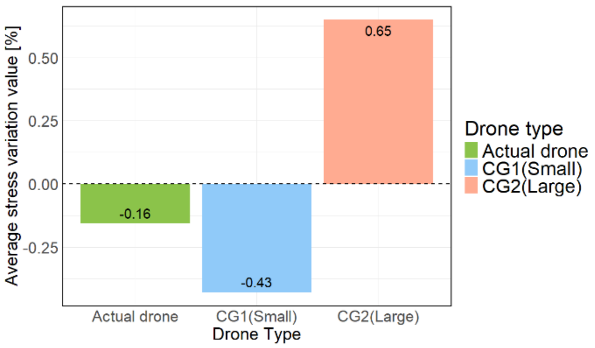

Fig.10　Average stress variation values (N=5).

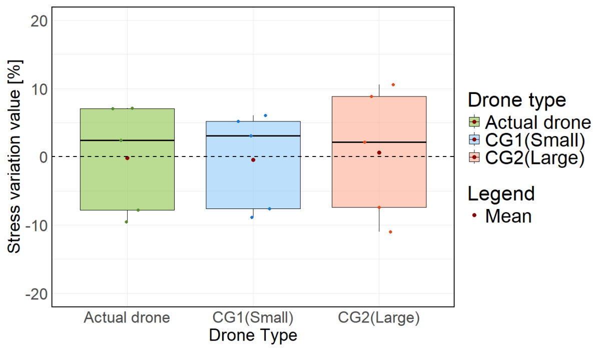

Fig.11　Distribution of the stress variation (N=5).

5-2　Discussion

As mentioned in Section 5-1, the participant who exhibited an unusually high stress change value for CG1 likely experienced significant stress from factors unrelated to the drone itself. Since the primary aim of this experiment is to evaluate the discrepancy between the actual and CG drones based on stress levels, it cannot be confidently stated that the data from this participant, with an extremely high stress variation value for CG1, are entirely reliable. Therefore, Figs.10 and 11 present the average stress variation values and the distribution of stress variation after excluding the data from this participant. The deviation values calculated from Fig.10 are $D_A^1 = 0.27$ and $D_A^2 = 0.81$, indicating that the smaller CG drones have smaller deviation values than the larger CG drones. Furthermore, because y_A^1 (CG1) and y_A^2 (CG2) encompass y_A^0 (actual drone), it is suggested that adjusting the size of the CG drones could bring the deviation value closer to zero. However, because there is no guarantee of a linear relationship between the size of the CG drones and stress levels, the data from Fig.10 only indicates that the average stress variation value for the actual drone lies between those for CG1 and CG2. Therefore, it is necessary to explore methods for reducing the deviation value by conducting experiments with an increased variety of CG drones of different sizes.

In this experiment, the small sample size led to individual participant data significantly influencing the overall results. As shown by comparing Figs.8 and 10, the differences in sample size caused substantial variations in the outcomes. Therefore, we believe that increasing the sample size in future experiments will yield more reliable results, less affected by individual data points. If similar results to those in Fig.10 can be obtained with a larger sample, it may be possible to adjust the size of the CG drone to reduce the deviation from the actual drone. Moreover, if the deviation can be minimized to near zero, it will open the possibility of developing a simulator capable of accurately assessing the stress levels associated with drones.

Contrary to the hypothesis that the average stress variation for an actual drone would be positive, the experiment produced negative values. This may be due to the fact that many participants were recruited from within the laboratory and were already familiar with drones, leading to a reduced sense of stress. Additionally, it is possible that the stress from the pre-experiment tension exceeded the stress induced by the drone flight.

6. Future prospects

The results of this experiment suggest that it is feasible to design an appropriate experimental environment for researching the social acceptance of next-generation aerial vehicles. These findings indicate that it may be possible to develop an experimental setup to investigate the effects of stress, even with drones replacing flying vehicles. However, the results of this study were significantly influenced by the sample size and the fact that participants were already familiar with drones in their daily lives, which limits the definitive conclusions that can be drawn. In future experiments, we plan to increase the sample size and target individuals unaccustomed to drones in their daily lives. This approach is expected to yield more reliable results than those obtained in this study. Additionally, while this experiment compared the actual drone with CG1, a small-scale CG drone, and CG2, a large-scale CG drone, future studies should include a CG drone of the same size as the actual drone. This would allow an investigation into whether there is any inherent discrepancy in the stress levels between the actual and CG drones. By incorporating a same-size CG drone, researchers could assess not only the presence of discrepancies but also how to adjust the size of CG drones to minimize deviations from the actual drone. Furthermore, evaluating the discrepancies by varying both the size and noise levels of the CG drones could offer new insights and deepen our understanding of the factors influencing the social acceptance of UAM.

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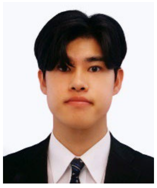

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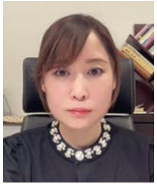

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Letter

映像伝送中継局向け固定翼 UAV における旋回半径偏差と機首方位角を用いた高精度旋回経路追従制御技術の研究

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近年，無人航空機（UAV）は，様々なサービスへの利用が広がっている。中でも固定翼 UAV は長時間飛行や広域観測に有利である。固定翼 UAV の利用例の 1 つである，無線中継局を実現するには指定した円経路に沿って正確に旋回し続ける必要がある。そこで，本稿では固定翼 UAV の旋回半径制御系と機首方位角制御系から構成される新たな高精度旋回経路追従制御系を提案し，6 自由度シミュレーションによりその制御系が正常に動作することを確認するとともに，さらに飛行実証を行った結果を報告する。

Keywords: 固定翼 UAV，旋回，ロール角，方位角，飛行実証

Highly Accurate Turn Path Tracking Control Technology for Fixed-wing UAV Using Radius Deviation and Nose Heading Angle to Realize Video Transmission Relay Station

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Unmanned Aerial Vehicles (UAV) have recently been used to provide many kinds of services, among them fixed-wing UAVs are advantageous for long flights and wide-area observations. In order to realize wireless relays station by the UAV, the UAV should continue to accurately turn along a predetermined circular path with its radius specified. To realize the path, we propose a new turn path control system that consists of radius deviation control and nose heading angle control on the UAV, and describe simulation results by which it is confirmed that the proposed control system worked well. And finally, we describe results of the flight verification experiment.

Keywords: Fixed-wing UAV, turning, roll angle, yaw, Flight verification

1. Introduction

In recent years, the use of unmanned aerial vehicles has advanced, and research and development are underway to provide future services in the fields of agriculture and forestry, such as crop pest control, farmland monitoring, surveying disaster areas, terrain measurement, transporting supplies, and radio relay for securing communication links [1]. In this situation, we have proposed a video transmission relay system using a fixed-wing UAV as a relay station, as shown in Fig.1. Currently, multi-copters, which are rotary-wing UAVs, are often used for observation. On the other hand, fixed-wing UAVs are more advantageous when observing large areas over long distances in a short period because they have a long endurance. Focusing on its long endurance, fixed-wing UAVs can be used as a wireless relay station for the video transmission relay system by making it turn along a predetermined circle path accurately and continuously. There are many papers on turning techniques. For example, in paper [2], flexible path following is essential when fixed-wing UAVs are used for various missions such as surveillance and disaster applications, so they aimed to follow complex paths, including curves, and confirmed their performance through both simulations and flight experiments. Also, in paper [3], a method is proposed to generate a turning path for a fixed-wing UAV without sacrificing maneuverability and safety, with the goal of enabling the fixed-wing UAV to safely perform its mission in a confined space. Also, in paper [4], a control method for rapid direction change is proposed for the purpose of carrying out missions such as surveillance and search and rescue without compromising the advantages of fixed-wing UAVs, such as high speed. However, none of them describe how to make the UAV turn along the predetermined circular path accurately and continuously.

Therefore, we propose a new turn path tracking control system that makes use of the target nose heading angle and turning radius. By using the control system, at first, computer simulations were carried out for small fixed-wing UAV so as to confirm its validity. Then, flight experiment was conducted to verify the control system.

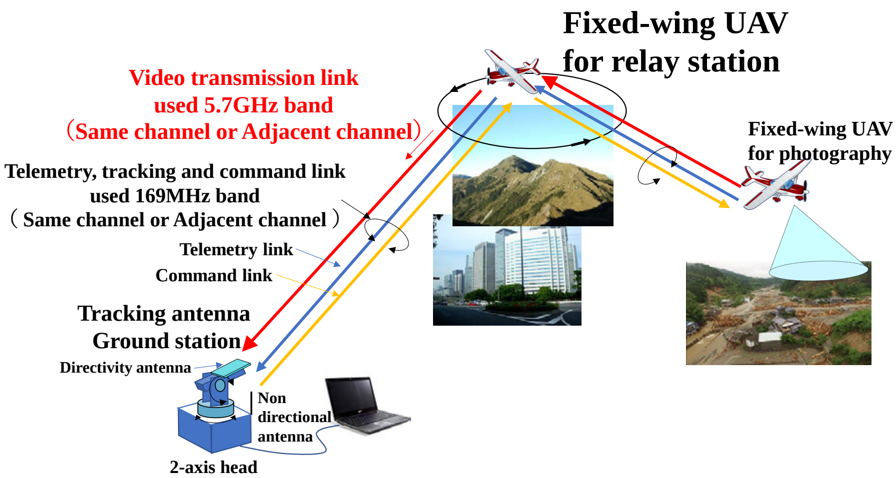


Fig.1 Image of video transmission relay system using fixed-wing UAVs.

2. Conventional turn path control and problems

The authors aimed at achieving highly accurate turn path tracking by using two control systems. One is a roll angle control system focusing on lateral force balancing by aileron operation. The other is a turn radius control system of which rudder command is given by the difference between the target turn path radius and the actual turn radius [6]. After confirming the validity of the method by computer simulation, the flight experiment was carried out as shown in Fig.2. The red line shows the turning trajectory, which deviates significantly from the target path shown in black. The reason is that as the roll angle control system and the turning radius control system were designed independently, when the vehicle deviates significantly from the target turn path, the force generated by the roll angle control system offset the force generated by the turn radius control. That is to say, when the UAV is located inside the target turn path, the force by the roll angle of which radius path is cancelled out by the force of the rudder angle, resulting in the turn radius which is larger than that of the target turn path.

In the same way, when the UAV is located outside the target turn path, the force generated by the rudder is added to the force generated by the roll angle, therefore, that results in a small turn path.

In addition, even though the simulation was successful in turning in the method we proposed [6], the successful accurate turning could not be reproduced in the flight verification experiment. We confirmed that this is due to the expansion of the initial deviation caused by the delay in the control system that occurs immediately after the start of the turn. In fact, simulations performed with our methods, do not take initial deviations into account. Therefore, this time, the proposed methods simulations including initial deviations we carried out to confirm convergence.

From above results, it is clarified that it was necessary to consider the balance adjustment between the roll angle control system and the turning radius control system which uses the rudder. Before investigating the method to design the balance adjustment, we explored to realize a highly accurate turn path tracking system by only roll angle control system based using deviation of both turn radius and heading angle.

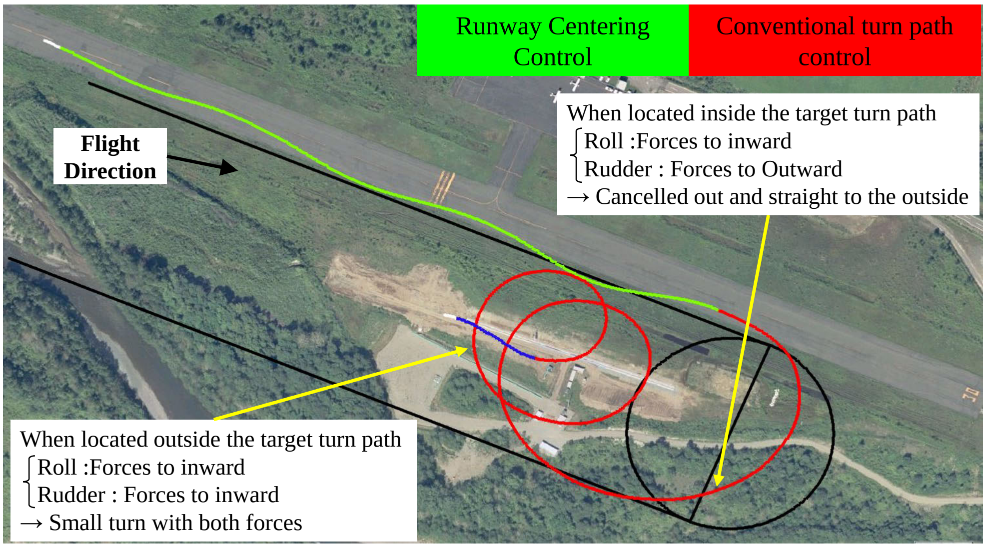


Fig.2 Flight experiment at shiraoi gliding port by conventional turn path control [6] technology.

3. Proposal of highly accurate turn path tracking control method

3-1 Control system policy and configuration

We propose a new control system to track the turning path accurately, which consists of a turn radius control system and a nose heading angle control system. Both control systems use the roll angle control system. The commands to the nose heading angle control system are a sum of two kinds of nose heading angle. One is the ideal nose heading angle ψ_{tan}, which is measured from true north to which the airplane should be directed corresponding to position of the airplane. The other is the nose heading angle ψ_{cmd} which is calculated by the deviation from the target radius R_{cmd} and the actual radius R. The sum of these nose heading angles is converted to roll angle command ϕ_{cmd} through PID parameter. Therefore, the turn radius control system is incorporated as an outer loop of the nose heading angle control system to reduce the turn radius deviation to zero and the roll angle control system is incorporated into the inner loop of the nose heading angle control system as shown in Fig.3.

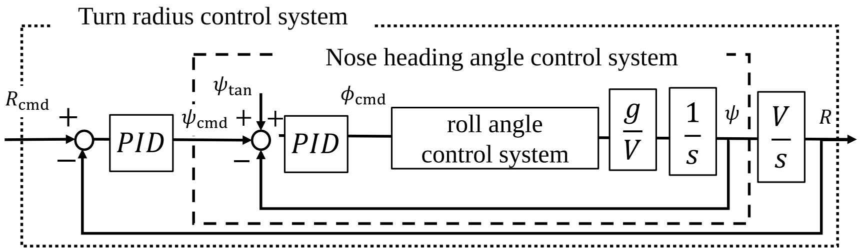


Fig.3 Block diagram of turn path tracking control system.

3-2 Relationship between turning radius deviation and nose heading angle

From Fig.4, after a radius deviation ΔR is defined as a difference between the target turn radius and the actual turn radius, from Fig.4 the relationship between the radius deviation ΔR and the nose heading deviation $\Delta\psi$ measured from the line parallel to the tangent line of the turn circle can be expressed as shown in Eq. (1)

$$\Delta\dot{R} = V_L \sin\Delta\psi \tag{1}$$

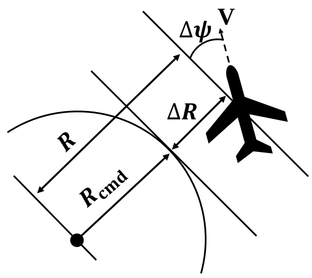


Fig.4 Relationship between turning radius and nose heading angle.

3-3 Derivation of ideal nose heading angle ψ_{tan}

Next, the ideal nose heading angle ψ_{tan} at the current position of the airplane is derived. First, in Fig.5, l_1 is the line connecting the turning center and the current position of the airplane, l_2 is the tangent line at the intersection of l_1 with the target turning path, and l_3 is the line extending to the true north direction from the turning center. The angle between the x-axis and the true north is ε.

The ideal nose heading angle ψ_{tan} is the angle between l_2 and l_3. To obtain the ideal nose heading angle ψ_{tan}, first it is necessary to determine the inclination θ of l_1. The angle θ can be derived from the current position (x_t, y_t) and x coordinates axis with the center of circle as its origin as shown in Eq. (2). Next, the angle λ between the tangent l_2 and the x coordinate axis can be derived as shown in Eq. (3) using the angle θ.

$$\theta = \tan^{-1}\left(\frac{x_0 - x_t}{y_t - y_0}\right) \tag{2}$$

$$\lambda = \theta + \frac{\pi}{2} \tag{3}$$

From the above, the ideal nose heading angle ψ_{tan} can be derived as shown in Eq. (4) using the angle ε between the x coordinate axis and the true north, and the angle λ in Eq. (3).

$$\begin{aligned}\psi_{tan} &= -(\lambda + \varepsilon)\\ &= -(\theta + \tfrac{\pi}{2} + \varepsilon)\end{aligned} \tag{4}$$

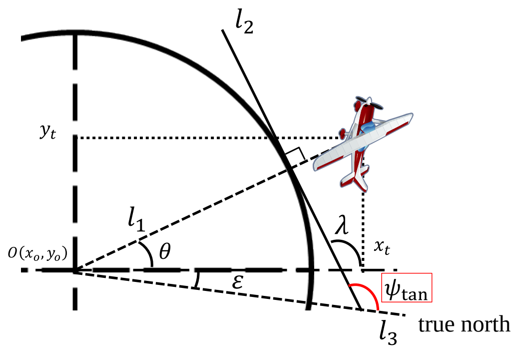


Fig.5　Tangent angle on the target path obtained from the flight position.

4. Simulation

The validity of the proposed turn path tracking control system is evaluated by computer simulations. In simulations, all actual control systems such as velocity control system, altitude control system and the turn path tracking control system are incorporated. All controller in those control systems use PID elements. Also, the feedback rate for simulation is 25 [Hz].

4-1　Controlled airplane

Assuming the flight experiment, data of an actual model airplane are used. The airplane is a low-wing type one and driven by fuel engine and has a mass of about 5.5 kg, a total length of 1.7 m, and a wingspan of about 2 m. The picture of the model airplane is shown in Fig.6.

Fig.6　Model airplane.

4-2　Simulation conditions

At first, the aircraft will fly in a straight line for 50 seconds to keep the airplane stable before entering into a circling flight. In the simulation, the turn radius, the altitude and the air velocity are targeted to be those as shown in Table 1. Besides, the criteria to judge whether the proposed control system works well is set in advance. For the first circle, the deviation of the turn radius is set to within ±14 m, which is 20% of the target radius, by taking into account for the transition such as rise-up and overshoot in control systems. For the final circle, the deviation is set to be ±6 m, taking into account the sensor errors used onboard systems of the actual model airplane. Those errors are specified as standard deviations shown in Table 2.

Simulations were carried out for following three conditions to confirm the convergence of the control system. The first is a no-wind condition. This was conducted to verify the stability of the control system. The second is a steady wind (3 m/s) condition parallel to the x coordinate axis. This was conducted to verify the performance in a disturbing wind environment. The third is the condition that has an initial deviation of 10 meters to confirm the performance of the convergence.

Table 1 Simulation conditions.

Target turning radius	70 m
Target altitude	100 m
Target air velocity	25 m/s

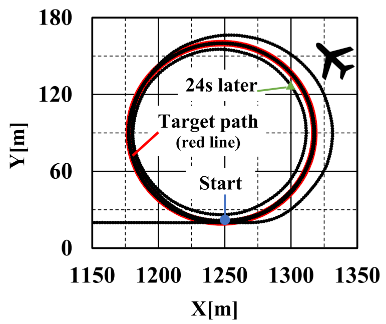
Table 2 Sensor error.

Attitude angle	0.5 deg.
X, Y direction	3 m
Altitude	0.2 m
Velocity	0.17 m/s

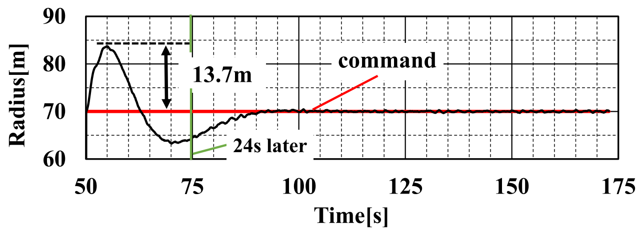
4-3 Simulation results

The flight trajectory obtained from the simulation and the time histories of the turning radius are shown below. Also, while the flight trajectory is expressed in three dimensions in Reference 6, it is expressed in two dimensions in this paper to make the trajectory at the time of turning easier to understand.

At first, simulations were carried out under no wind conditions shown in Fig.7. From Fig.7, the maximum turn radius deviation for the first circle was 13.7 m and the radius converged to ±0.6 m in about 24 s from the start of the turn, which was within the target value.



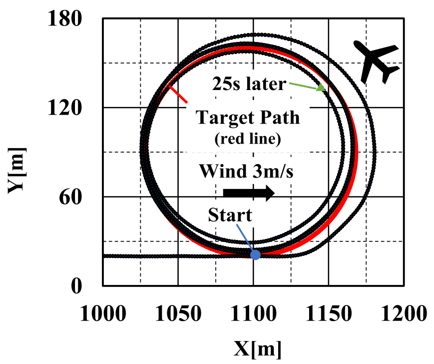
(a) Flight path



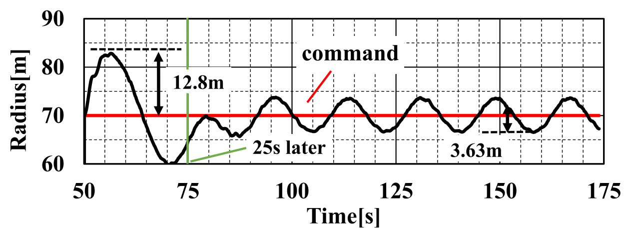
(b) Time histories of the turning radius

Fig.7 Simulation results (no wind).

Then simulations were carried out for a steady wind of 3 m/s as shown in Fig.8. From Fig.8 the maximum turn radius deviation for the first circle was 12.8 m, and the final deviation was 3.6 m, which was within the target range. It was also confirmed that the radius converged within ±6 m of the target radius in 25 s from the start of the turn.



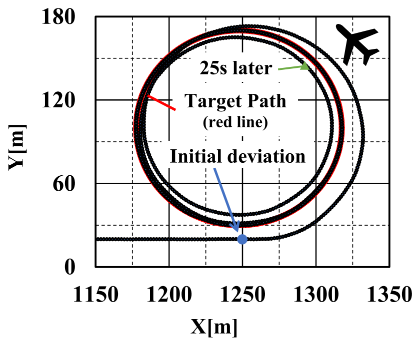
(a) Flight path



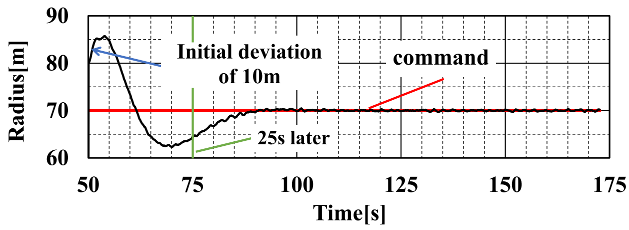
(b) Time histories of the turning radius

Fig.8 Simulation results (steady wind of 3 m/s).

Finally, the simulation was performed with an initial deviation of 10 m as shown in Fig.9. From Fig.9, it was confirmed that the radius converged within ±6 m of the target radius in 25 s from the start of the turn.



(a) Flight path



(b) Time histories of the turning radius

Fig.9 Simulation results (initial deviation of 10 m with no wind).

5. Flight verification experiment

A flight verification experiment was conducted using the proposed control system. The target airplane (Fig.6), same as simulation, was mounted with a microcontroller board and an autonomous control program written in C language was executed. Also, the feedback rate is 25 [Hz], the same as simulation. The airplane first follows a straight path and after passing a given point switches to a turning flight to follow a circular path with a radius of 70 m. The airplane then flew to follow a straight path in the opposite direction after completing 5.5 laps of turning flight. The actual flight path results are shown in Fig.10 and the time history of the turning radius is shown in Fig.11. From Fig.10, it can be found that all flight phases follow the target turn path. Fig.11 shows that the turning radius generally follows the command, although there is some vibration around target of 70 m. Also, the average deviation of the radius was 7 m throughout the turn flight. This result was satisfactory considering the sensor error used, control error.

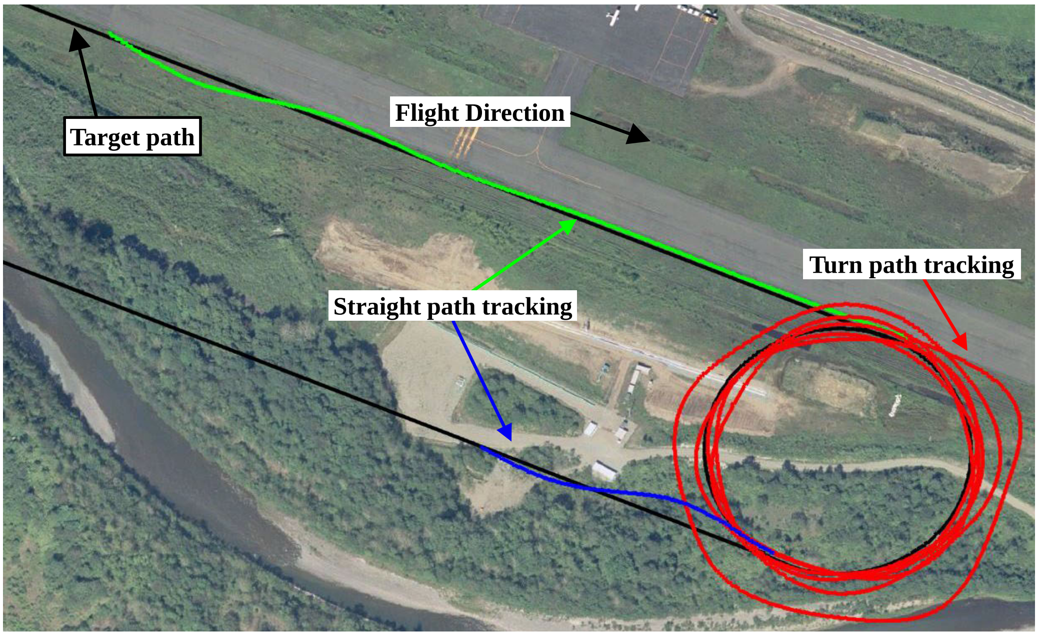


Fig.10 Flight experiment.

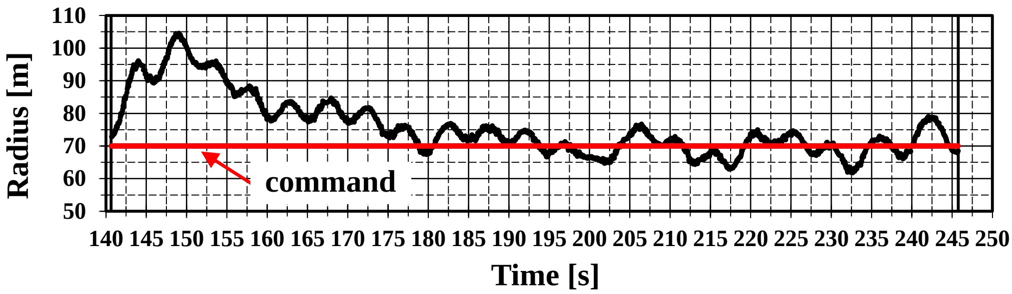


Fig.11 Time history of turning radius.

6. Conclusions

To realize highly accurate turn path tracking, we proposed a new control system to use radius deviation and nose heading angle. The feature of the proposed control system uses two nose heading angles derived from the current position of the airplane and the radius deviation. After simulations, it was confirmed that the airplane could turn within the target deviation against the target turn radius under no wind and a steady wind of 3 m/s.

Finally, flight verification experiment was conducted using the proposed control system, and a stable turn of 5.5 laps was achieved.

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Strategical Perspectives on Market Entry of Urban Air Mobility (UAM) in Japan

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This paper explores the market penetration of urban air mobility (UAM) in Japan, a rapidly developing field with the potential to revolutionize transportation in cities worldwide. While there is significant interest in exploring the possibilities of UAM in Japan, its successful implementation requires the consideration of various factors, such as sustainability goals, social acceptance, and the creation of a suitable ecosystem. This research aims to provide insights into the key strategic considerations for UAM stakeholders seeking to enter and penetrate the Japanese market, as well as how these considerations differ for new entrants compared to established companies.

Keywords: Urban Air Mobility (UAM), Market Penetration, Sustainability, Social Acceptance, Ecosystem Creation, Strategic Considerations, Regulatory Environment, Japan Cultural Context, UTM, UAM, Drone, Mobility

1. Introduction

Urban air mobility (UAM) is a rapidly developing field with the potential to revolutionize transportation in cities around the world. In Japan, a country with a highly developed transportation infrastructure and a keen interest in technological innovation, there is significant interest in exploring the possibilities of UAM. The Japanese government has already taken steps to encourage the development of UAM, such as establishing the public-private UAM promotion council in 2018 [1]. To ensure the successful implementation of UAM in Japan, it is crucial to consider factors such as social acceptance, sustainability goals, and the development of a comprehensive ecosystem and effective market penetration strategy.

The study of urban air mobility and the development of ecosystem and market penetration strategies are becoming increasingly important as cities seek more sustainable and efficient transportation solutions. Japan, with its highly urbanized environment, is a promising market for UAM. This paper aims to contribute to the existing body of knowledge by exploring the key considerations for UAM stakeholders seeking to enter and penetrate the Japanese market.

To achieve these objectives, this study seeks to answer two fundamental research questions:

1. What are the unique challenges and opportunities for UAM stakeholders seeking to penetrate the Japanese market, and what strategies can they adopt to promote buy-in and foster a sense of collective responsibility in Japan?
2. What are the key strategic considerations in terms of the ecosystem for UAM stakeholders seeking to integrate with Japan's existing transportation network, and how do these considerations differ for new entrants such as start-ups compared to established companies?

Through qualitative analyses, this research aims to contribute to the understanding of the challenges and opportunities for UAM in Japan and shed light on how UAM can fit into Japan's existing transportation network and address its particular challenges.

2. Literature review

2-1 Theoretical framework

The theoretical framework for this literature review focuses on several key concepts: urban air mobility (UAM) within the mobility as a service (MaaS) paradigm, transportation innovation, technological advancement, and societal change.

UAM refers to the concept of using vertical take-off and landing (VTOL) aircraft to provide on-demand transportation services in urban areas. It is a trending research topic globally [2] and is closely monitored by major consulting firms [3,4].

Transportation innovation is critical for UAM, involving the development of new technologies and business models to make UAM a reality [5]. Technological advancements are essential for creating safer, more efficient, and more affordable aircraft and infrastructure. Societal change and social acceptance are also crucial, as UAM requires shifts in attitudes and behaviors towards transportation and urban development [6,7].

2-2 UAM ecosystem

An ecosystem, as defined by Armour, includes a wide range of stakeholders such as city, regional, aviation, and environmental authorities, as well as drone and air taxi operators, all crucial for UAM's successful planning, integration, and operation [8]. This ecosystem encompasses government agencies, transportation authorities, aviation and environmental authorities, and UAM operators [9]. Companies like Volocopter and E-Hang have issued white papers outlining their ecosystem strategies [10,11].

2-3 Sustainability goals and social acceptance

Sustainability is a critical consideration for UAM development, given the aviation industry's contribution to greenhouse gas emissions [12]. Battery technology, although promising due to breakthroughs in energy density, still presents challenges in terms of environmental impact and recycling [13,14].

Social acceptance is vital for UAM's success. Public perception, including concerns about noise pollution, safety, and privacy, plays a significant role in UAM adoption [7,3]. Ensuring social fairness is also important, as highlighted by the scaling model's impact on public acceptance [15].

2-4 Market penetration strategy and ecosystem creation

Successful UAM services depend on effective market penetration and ecosystem creation strategies. Various studies have examined these strategies, identifying opportunities for UAM providers to gain market share and create viable ecosystems [16]. In Japan, studies have identified distribution and cultural challenges, such as high entry costs and close business linkages, as significant barriers to market entry [17].

2-5 Market size references

As of September 2021, Japan's helicopter market was valued at approximately $700 million USD (Statista, n.d.). In fiscal year 2020, Japan's aviation industry supported over one million jobs and contributed nearly $83 billion to GDP [19]. The UAM market is projected to reach 2.5 trillion yen by 2040, assuming significant expansions in the aviation and travel markets [20].

2-6 Innovation and government initiative in Japan

Japan has a history of technological innovation, driven by government initiatives such as the Science and Technology Basic Plan [21]. In the context of UAM, METI has published a roadmap for UAM development, regularly updated to guide the industry's growth [22]. Japan's strong manufacturing sector, including battery and motor companies, plays a crucial role in UAM's supply chain development [23].

Japan is also investing in sustainability, focusing on clean technologies and the environmental impact of new products [24]. Despite these initiatives, Japan faces challenges such as an aging population, which affects the workforce and economy [25].

3. Research methodology

3-1 Research design and approach

An exploratory case study approach was chosen to investigate the strategy for implementing UAM in the Japanese market. This approach allows for a comprehensive understanding of the social, cultural, and economic factors affecting UAM implementation in Japan.

3-2 Questionnaire rational

Data were collected through semi-structured interviews, covering four main parts related to UAM implementation in Japan: Japanese innovation, sustainability goals, social acceptance, ecosystem creation, and market penetration strategy.

3-3 Data collection methods

A total of 21 interviews were conducted with various stakeholders, including OEMs, operators, research institutes, trading companies, insurance providers, and others. Interviews were recorded and transcribed, ensuring a broad perspective on the Japanese UAM ecosystem. The interviewees were carefully selected from organizations that play important roles in the Japanese Urban Air Mobility (UAM) ecosystem. This includes trading companies, OEMs, operators, academics, local government entities, insurance companies, and banks. Each of these stakeholders contributes uniquely to the ecosystem—through financing, vehicle design, operations, regulatory development, infrastructure support, public acceptance initiatives, and funding. Their collective insights provide a broad and comprehensive understanding of the challenges and opportunities in UAM development. This selection was made to ensure a holistic perspective, fostering collaboration and supporting the creation of an integrated framework for the safe and sustainable growth of UAM in Japan.

Table 1 Definition of the acronyms in Table 2.

Acronyms	Meaning
OEM	One Equipment Manufacturer
RI	Research Institute
OP	Operator
TC	Trading Company
BK	Bank
INS	Insurance
MC	Municipality
0TH	Others, Maintenance, Building Manufacturer, Drone Company

Table 2 Overview of interview partners.

Acronym	Classification	Role of Interview Partner	Interview Duration (min)	Location	Interview Date (dd.mm.yy)
OEM 1	Helicopter Firm Established	Senior Maneger(*)	110	On-site	23.11.2022
OEM 2	UAM Firm: New Entrant	Director	48	On-site	30.11.2022
OEM 3	Helicopter Firm: Established	Vice-President, CTO	65	On-site	02.12.2022
OEM 4	UAM Firm: New Entrant	CEHR, HR Manager(*)	46	Online	02.12.2022
OEM 5	Helicopter UAM Firm Established	Strategy Manager	40	Online	09.12.2022
RI 1	Academician Expert	Emeritus professor	53	On-site	29.11.2022
RI 2	Academician Expert	Ph.D. Executive Advisor, Fonner Professor	60	On-site	01.12.2022
RI 3	Academician Expert	Urban Air Mobility Research laboratory UAM Startup CEO & Head Airframe Head Airframe	66	Online	15.01.2023
RI 4	Academician Expert	Project Associate Professor	54	Online	15.01.2023
OP 1	Operator Established Airliner	Air Mobility Project Director	67	On-site	01.12.2022
OP 2	Operator Established Airliner	Air Mobility Creation Leader	65	Online	30.01.2023
OP 3	Operator Established Helicopter Operator	CEO(*) Head Marketing, OEM company	57	On-site	02.02.2023
TC 1	Trading Company New Entrant in UAM business	Assistant General Manager (*)	61	On-site	01.12.2022
TC 2	Trading Company	Leader, New Entrant in UAM business	54	Online	21.12.2022
MC 1	Municipality: Prefecture	Digital Business Promotion Division Leader (*)	58	Online	15.12.2022
BK 1	Investment Bank	Vice President	60	On-site	02.12.2022
IN 1	Insurance Company	Managers (*)	69	On-site	02.12.2022
PR 1	Press Agency: Journalist	Deputy Editorial Director, Digital	54	Online	03.02.2023
OTHI	Others: Maintenance Company	General Manager, Adviser(*)	59	On-site	30.11.2022
OTH2	Others: Airport Building Manufacturing Company	Assistant General Manager, Sales representative (*)	38	On-site	01.12.2022
OTH3	Others: Drone Company	CTO	43	Online	30.11.2022

Note that (*) indicates that the interview was conducted with two interview partners.

3-4 Data analysis methods

Qualitative content analysis was used for data analysis, focusing on stakeholders' perceptions and experiences regarding social acceptance and strategic considerations for UAM integration into Japan's transportation network.

4. Findings

4-1 Challenges & opportunities to the implementation of UAM in Japan

By exploring both the challenges and opportunities, this section aims to provide a comprehensive understanding of the UAM market in Japan. Additionally, the section will examine strategies that UAM stakeholders can adopt to promote buy-in and foster a sense of collective responsibility among stakeholders in Japan.

4-2 Identified challenges among the study stakeholders' group

4-2-1 Cultural and social challenges

A Press Journalist (PR 1) noted, "Fifty years ago, we had nothing. After World War II, our society and cities were destroyed... There were a lot of risk-takers and many entrepreneurs like the founder of HONDA, SUZUKI, Panasonic, and SONY." However, today, the environment has shifted to a risk-averse mentality, focused on safety and comfort. This sentiment is echoed by a trading company manager (TC2): "Innovative approaches appear conservative to us... it is not in the culture to try new things like this (UAM) before the others."

4-2-2 Social acceptance

The perception of flying vehicles as exclusive and inaccessible is a significant barrier. An academic (RI1) remarked, "Social fairness is a significant issue in Japan... there is significant opposition from shareholders and the general public towards companies owning business jets." The general public views flying as an infrequent activity, making air travel seem distant and inaccessible. An operator (OP 1) mentioned, "The general public feels that flying is something they do once a month or once a year."

4-2-3 Regulatory challenges

The lack of a regulatory framework is a significant obstacle. A director of an investment bank (BK1) highlighted, "If the FAA and EASA are doing the rulemaking... it is impossible for Japan to take the lead in this area." This sentiment is echoed by an OEM (OP2): "The need for regulations around low altitude utilization... is essential for the successful implementation of UAM." Additionally, Japan lacks regulatory expertise, and stakeholders are concerned about the country's ability to develop UAM regulations independently.

4-2-4 Technological challenges

Technological limitations, particularly battery and technology issues, pose additional challenges. An OEM participant (OEM3) noted, "The most problematic part of UAM is the battery. Once the battery issue is resolved, UAM can be put into practical use." Achieving sustainable mobility requires addressing the entire lifecycle of the battery to minimize environmental impact.

4-2-5 Market demand and economic challenges

Demand, profitability, and cost are significant concerns. Japan's relatively low traffic congestion and stable population growth reduce the perceived need for UAM solutions. An investment bank vice-president (BK1) observed, "In Japan, there are not enough traffic jams to justify the use of those taxis." This challenge is compounded by the need to achieve a competitive price point while ensuring profitability. An academic expert (RI4) stated, "There are not many customers willing to pay for a vehicle that is more expensive than a taxi."

4-3 Identified opportunities among the study stakeholders' group

4-3-1 Government leadership and incentives

Government leadership and incentives play a crucial role. An academic (RI1) observed, "Support from local governments is necessary." Public-private partnerships can help finance UAM infrastructure projects. BK1 emphasized, "In order to guarantee the top-line revenue, local governments will likely need to provide some level of assurance... public-private partnerships such as PPP, PFI, and private finance initiatives will likely be necessary."

4-3-2 Social benefits and cultural motive

UAM has the potential to provide social benefits and foster regional development. Stakeholders emphasized the importance of using UAM for emergency medical services and disaster relief, which could enhance social acceptance. An operator (OP2) suggested that UAM could solve regional social issues and contribute to economic growth by creating employment opportunities and attracting new residents. OEM1 noted the benefits of ensuring doctor rotations to local communities: "If, for example, an eye doctor comes on Mondays and a surgeon comes on Tuesdays, wouldn't people in rural areas be happier with that?"

4-3-3 Positive marketing and Japan branding

Positive marketing and leveraging Japan's strong brand image can foster social acceptance. The involvement of well-established Japanese airlines like ANA and JAL can enhance customer confidence. An operator (OP2) stated, "The general customers are more likely to feel safe and secure if it is operated by ANA or JAL." This sentiment is reinforced by partnerships such as Joby's collaboration with Toyota, which emphasizes quality and safety.

4-3-4 Economic impact

UAM can promote regional revitalization and economic growth by creating employment opportunities and attracting new residents. Trading companies believe that air mobility could provide tangible benefits to society. TC2 remarked, "Using this kind of air mobility to support residents in remote islands with poor access... will be a tangible benefit to society."

4-4 Key factors influencing the successful creation of an ecosystem and market penetration strategy for UAM service providers in Japan

4-4-1 Ecosystems in a Japanese environment

The definition of the UAM ecosystem has been given in paragraph 2.2. Due to the availability of resources on the different solutions such as Volocity, VoloIQ, and Voloport, the ecosystem conceived by Volocopter has been taken as a reference during the interviews. Stakeholders concurred on how difficult it would be for one company to uniformly implement an ecosystem in Japan. The manager of a major Japanese company (INS1) believes that presenting a packaged, integrated ecosystem model would be beneficial for promoting new entry into the market.

A University Professor (RI2) noted, "It is natural that a business ecosystem is necessary, and this figure is not sufficient as it does not yet include many stakeholders." The CEO of a Japanese operator sees potential business development: "If we propose it to Volocopter, we can handle the ports, operations, and maintenance... there is potential for us to grow."

4-4-2 Market entry strategies

Stakeholders link Volocopter's ecosystem vision to a first-to-market strategy. Being the first to market may require a company to do everything themselves, from manufacturing to service delivery. An OEM strategy manager (OEM5) noted, "If you want to market yourself as the first to market, then you must do everything." However, as the market develops, companies can specialize and focus on their core competencies.

The failure of foreign companies like Uber in Japan was frequently mentioned. The manager of a trading company (TC2) explained, "When Uber came to Japan, they didn't do any groundwork or collaborate with the taxi industry... I think it might be difficult for this (UAM) to really take hold in Japan." An OEM director (OEM2) noted, "Uber couldn't enter Japan... they are doing dispatch apps with Japan Taxi." Successful entry requires understanding and adapting to Japanese market specificities.

4-4-3 Business development, established companies vs new entrants competition & Japanese market

Interviews revealed that the UAM market will not reshuffle the existing market but will expand it. An academic professor (RI3) noted, "The market itself will expand... helicopter operating companies may operate UAM." A new entrant OEM manager (OEM4) sees potential for new entrants due to lower pilot training costs: "If the cost of training pilots becomes much lower with flying cars, there will be room for many companies to enter."

Trading companies will play a significant role by potentially acquiring established helicopter operators and planning to operate vertiports. An academic professor (RI2) indicated, "Trading companies can gather funds and acquire helicopter companies." Development banks also observe this trend: "Sojitz recently acquired Okayama Aviation."

4-4-4 Vertiport considerations in Japan

Doubts have been raised regarding the potential monopoly of one company over the development of vertiports. A major airlines manager (OP2) stated, "It would be better to have them as public facilities, where various types of aircraft can land." An academic professor (RI1) noted, "If the government is responsible for the initial development, the system will be available to anyone." A manager from an airport facility building company believes the government will establish rules for public facilities but will decide for places integrated into current airports.

This same manager explains that there will be three different types of ports - small, medium, and large. "For large-scale facilities, build at airports or ports; for mid-sized ports, build in tourist destinations; for small-scale facilities, build on rooftops of buildings or in small towns."

4-5 Summary of use cases with potential in Japan

During the interviews, the participants identified the Seto Inland Area as a promising region for UAM implementation. A major Japanese airline director (OP2) indicated potential in regions that could not accommodate helicopters in the past: "In the past, Japan had a commuter helicopter business in areas like the Seto Inland Sea... it's a feeling that something new will be born."

A trading company manager (TC1) remarked, "It's hard to imagine many flying vehicles over Tokyo right away. Securing routes in places like the Seto Inland Sea might lead to a sense of security." The director of an investment bank (BK1) concurred, "The Seto Inland Sea is definitely the right choice." Using UAM for tourism is seen as a viable initial application, eventually expanding to emergency transport and other uses.

The METI and the Development Bank of Japan have detailed potential use cases in the Setouchi area, including maps and tables comparing distances and access times by cars, trains, and UAM.

These findings underscore the importance of a collaborative approach involving government, industry, and the public to overcome challenges and leverage opportunities for successful UAM implementation in Japan.

5. Discussion

5-1 Summary of findings

5-1-1 First research question

The aim of this research was to explore the different stakeholder perceptions of social acceptance in Japan and identify the associated challenges and opportunities. The research identified several key themes related to stakeholder perceptions of social acceptance and effective strategies for promoting buy-in and fostering a sense of collective responsibility. These themes include stakeholders' concerns regarding the exclusive and inaccessible nature of EVTOL, as well as potential issues with demand, profitability, cost, regulatory hurdles, battery, and technology limitations.

Additionally, the unique characteristics of Japanese society and industry, such as the emphasis on perfectionism and risk-aversion, were identified as relevant factors. To foster social acceptance, several effective opportunities that stakeholders in the UAM industry have been identified, such as following government or municipal leadership, utilizing positive marketing and Japan branding, offering community-wide benefits, and encouraging Japanese company contributions.

5-1-2 Second research question

The findings of this study on the key strategic considerations for UAM stakeholders seeking to integrate with Japan's existing transportation network reveal that stakeholders are not inclined to accept a monopoly by a single company within the ecosystem. This is due to the economic challenges posed by such a structure in Japan. Instead, the "First to Market" strategy encourages new entrants to develop and promote their ecosystems, while recognizing that, eventually, tasks will need to be divided among all stakeholders.

Moreover, the study highlighted that Japan is a unique market. Companies like Uber have failed to establish themselves here, not due to lobbying by existing business entities, but because of Japan's distinct regulatory, cultural, and business landscape. For instance, Japan's market places a strong emphasis on long-term partnerships, compliance with highly specific regulations, and societal alignment with new technologies. Foreign companies often struggle to adapt to these factors. This underscores the importance of paying close attention to the specific rules and cultural nuances of the Japanese market for effective market entry.

While the perception that there will be no reshuffling of the traditional aerospace industry in Japan was noted, the study suggests that this may not be entirely accurate. Instead of a complete reshuffling, gradual shifts are likely, particularly in the role of trading companies. These companies, traditionally focused on facilitating business transactions, may pivot towards operational roles in the UAM ecosystem, such as managing vertiports or directly engaging in UAM operations.

Thus, companies aiming to enter the UAM industry in Japan must remain flexible and prepare for potential shifts in the industry landscape. Understanding and adapting to Japan's unique market dynamics will be essential for long-term success.

5-2 Discussion and result interpretation

The Technology Acceptance Model for Disruptive Transport Technologies, adapted from the original TAM [26], and the Automation Acceptance Model (AAM) [27] provide useful frameworks for understanding the factors that influence the adoption and use of urban air mobility (UAM). These models include four key components: perceived usefulness, perceived ease of use, social influence, and facilitating conditions. In this discussion chapter, these components of the UAM framework and ecosystem will be used to analyze the findings.

5-2-1 The framework

<u>Social fairness / social acceptance</u>

The need for social fairness has been addressed by most stakeholders. This point aligns with current research, which states the need to scale the UAM market to ensure social fairness. Addressing challenges such as regulatory frameworks, safety and infrastructure standards, and community acceptance is critical for the growth and success of the UAM market in Japan. Overall, addressing the perception of flying vehicles as exclusive and inaccessible is essential for the growth and success of the UAM market in Japan.

Demand, profitability, and cost

The concern of not finding enough customers willing to pay for UAM services is a critical issue highlighted by the academic expert (RI4). The economic viability of UAM operations is highly dependent on their scalability. While Japan may not have enough traffic congestion to justify UAM as a solution to traffic problems, other potential use cases exist in rural and island regions, as well as for tourism. Progress in remote operation, automation, and battery technology could make UAM business models more sustainable and profitable in Japan by the 2030s.

Regulations

The regulation of UAM is a significant challenge for its adoption in Japan. The Japan Civil Aviation Bureau (JCAB) has eased regulations for flight testing and demo flights of UAM vehicles, allowing some OEMs to conduct successful demo flights. However, strict regulations regarding small aircraft and the need for a nuanced understanding of regulatory challenges remain obstacles. Continued efforts to align Japan's regulations with international standards are necessary.

Battery and technology limitations

The findings indicate that stakeholders, particularly OEMs, view battery technology as a major challenge for Urban Air Mobility (UAM) and emphasize the need for further investigation into its real impact on sustainability. This aligns with the current state of research, which highlights battery technology as a critical barrier to UAM implementation globally [13]. Despite recent breakthroughs, batteries still have significantly lower energy density compared to fossil fuel propulsion, impacting the vehicle's range, payload capacity, and overall performance.

Moreover, achieving sustainable mobility necessitates a comprehensive approach to the battery life cycle, including environmental impact and recycling. As noted by [14], the demand for batteries is projected to rise significantly, underscoring the importance of ensuring that UAM batteries are sustainable and circular—capable of being reused, repurposed, and recycled. The reduction targets for aircraft CO2 emissions are ambitious, with the International Civil Aviation Organization (ICAO) aiming for zero net CO2 emissions by 2050 [28]. This goal will similarly drive higher sustainability standards for UAM. Addressing these challenges requires ongoing research and innovation to make UAM a viable and environmentally friendly transportation option.

Japanese society and industry particularities

The findings highlight Japan's cultural emphasis on zero risk and perfection (TC2). Governmental agencies are motivated to link UAM development with the automotive sector, but the established rail industry may hinder UAM progress (OEM1).

The Japanese automotive industry, lagging in electrification, sees UAM as an opportunity for innovation. "Japan went with hybrids, while Europe and the United States went straight to EVs. Japan was left behind in terms of electrification, and the automotive industry feels a sense of crisis." Consequently, the Ministry of Economy, Trade and Industry supports UAM development (RI3). The term "flying car" (Sora Tobu Kuruma) resonates with Japan's automotive sector and has been popularized through media [29], although the public often views EVTOLs as "manned drones" [30] .

Japan's zero-risk culture, stemming from the Fukushima nuclear incident, can lead to caution in adopting new technologies (TC2,[31]). However, drones are already flying over homes, indicating progress in risk management (RI2). Lessons from the nuclear industry underscore the importance of proper risk evaluation for UAM.

5-2-2 The ecosystem

Government's roadmap

Findings indicate that Japan's UAM infrastructure development relies heavily on government leadership, local government support, and public-private partnerships. The Japanese government, particularly METI, has been proactive, organizing eight seminars since 2018 to advance UAM [22]. The METI roadmap, updated regularly, outlines a comprehensive plan for UAM development in three phases: initial (2018-2020), demonstration (2021-2025), and practical use (2026-2030).

The roadmap emphasizes UAM's potential to reduce urban congestion, improve disaster response, and enhance remote area accessibility. It sets a vision for "a society where people can move freely and safely in the air," focusing on regulatory reforms, infrastructure, technology development, and international cooperation. Key measures include establishing a legal framework, developing vertiports, conducting vehicle tests, and harmonizing global regulations.

Japan's approach, more comprehensive than EASA and FAA roadmaps, aims for a holistic UAM implementation, integrating infrastructure and technology advancements with regulatory and safety considerations. This broader scope suggests a more effective implementation process.

RI2 notes that despite limited venture capital, the government fosters corporate investment through its roadmap. The upcoming Universal Exhibition could further boost UAM visibility, attracting public interest, investment, and talent to Japan.

Market entry strategies

The timing of entry and the competitive landscape are crucial for companies entering the UAM market in Japan. The first-to-market strategy may require companies to do everything themselves in the early stages. However, as the market develops, specialization and collaboration become more feasible. Building local ecosystems and collaborating with local partners is essential for navigating Japan's unique market conditions.

Stakeholders landscape

The UAM market in Japan is a ground for competition between new entrants and established players. Major Japanese Aerospace OEMs are involved in UAM development but show less interest in developing their own EVTOLs, creating opportunities for new and foreign entrants [32]. Companies like Denso and Honeywell are expected to play significant roles in the UAM supply chain, developing motors and inverters through a long-term partnership [23].

Operators, such as JAL and ANA, are crucial due to safety concerns in Japanese culture. Smaller helicopter operators face competition from trading companies, which are new to the UAM market but established in traditional aerospace. Companies like Sojitz have started acquiring operators, indicating a strategic move into the UAM sector [33].

Foreign companies entering the Japanese UAM market should consider the competition landscape, partnerships with operators, and collaboration opportunities with battery and motor companies. UAM holds potential advantages for communities, addressing regional social issues, stimulating economic progress, and promoting growth [6]. UAM can aid during natural disasters, improve access to remote areas and medical facilities, and enhance tourism and business opportunities. Local communities play a vital role in managing UAM operations, especially in urban areas, with potential synergies with the drone industry, exemplified by TrueBizon's financial compensation system for flyovers [34].

Vertiport considerations

The development of vertiports should be public facilities accessible to various companies rather than being monopolized by one company. The involvement of the government in establishing rules for public facilities is crucial. Different types of ports (large, medium, and small) should be developed to meet the needs of various regions and use cases.

5-3 Limitation of the study & suggestions for future research

The study's findings are based on the perspectives of industry specialists, which could result in potential biases. As the interviewees were selected from organizations directly involved in the UAM ecosystem, their views may reflect an industry-centric outlook and may not fully capture concerns or skepticism from the general public or other independent stakeholders.

To mitigate this limitation, future research could include a broader range of participants, such as members of the general public, non-governmental organizations, and environmental advocates. A supplementary public survey could provide additional insights into social acceptance and concerns about UAM. Furthermore, clarification and communication of the definition of "flying car" may be necessary to enhance understanding and acceptance. A comparative analysis between Europe and Japan on social acceptance for UAM could also offer further valuable perspectives.

6. Concluding summary

This research focused on the potential of UAM in Japan, highlighting opportunities and challenges. Recommendations for addressing social fairness, safety, and regulatory issues include promoting community-wide benefits, positive marketing, and encouraging Japanese industry contributions. Collaboration with Japanese government agencies and trading companies is crucial for successful UAM implementation.

Recommendations:

1. Social Fairness: Address perceptions of exclusivity and inaccessibility by promoting community-wide benefits and positive marketing.
2. Technological and Safety Aspects: Communicate these aspects through public demonstrations and educational initiatives.
3. Japanese Industry Contribution: Develop a domestic supply chain for UAM components and involve Japanese industry in infrastructure development.
4. Market Entry: Partner with Japanese trading companies and establish strong relationships with municipalities.
5. Use Cases: Analyze the potential for UAM development in the Seto Inland area.

By following these recommendations and working collaboratively, UAM could become a reality in Japan, providing a new mode of transportation that benefits communities throughout the country.

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固定翼 UAV の短距離着陸を目的とした瞬時降下率最大化による減速旋回降下技術の研究

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近年無人航空機の利用が進む中，固定翼 UAV は高速・長距離飛行が可能であるため様々な分野での活用が検討されている [1, 2]。しかし，高速飛行を行う固定翼 UAV は着陸距離が増大する。この問題に対して本研究では通常の直線経路に沿って飛行速度一定で降下するグライドスロープに対して，複数回旋回飛行しながら減速と降下をする「減速旋回降下技術」を提案し，水平距離を短縮するとともにタッチダウン時の飛行速度を減少させることによるロールアウト距離の短縮を目指す。提案技術は高精度に旋回経路を追従する技術の上に，速度は一定の加速度で減速，飛行状態より計算したその瞬間でとれる最大の降下率で降下させる技術より構成される。本稿では，提案技術の 6 自由度シミュレーション結果及び，「高精度旋回経路追従技術」について飛行試験により検証した結果を報告する。

Keywords: UAV，旋回，減速，降下，着陸，シミュレーション，飛行試験

Study on Deceleration and Turning Descent Technology by Maximizing Instantaneous Descent Rate for Short-range Landings of Fixed-wing UAVs

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As the use of unmanned aerial vehicles has advanced in recent years, fixed-wing UAVs have been developed for use in various fields for their high-speed and long-distance flight capabilities [1, 2]. However, fixed-wing UAVs that fly at high speeds require a long landing distance. To address this issue, this study proposes a deceleration and descent technology that incorporates multiple turning maneuvers as opposed to the conventional glide slopes that allow for descent at a constant flight speed along a normal straight-line path. This approach can shorten the horizontal and roll-out distances by decreasing flight speed at touchdown. The proposed technology combines highly accurate turn path tracking control with the generation of commands for speed deceleration and the maximum achievable descent rate based on real-time flight status. Using the proposed technology, 6-DOF simulations are carried out to confirm its validity, followed by flight experiments to evaluate its performance.

Keywords: UAV, Turning, Deceleration, Landing, Descent, Flight simulation, Flight verification

Nomenclature

a	: Acceleration	T_{min}	: Minimum thrust of the UAV
$C_{L\alpha}$	: Lift curve slope	t_f	: Flare start time
D	: Drag force	V_a	: Initial flight velocity
g	: Gravitational acceleration	V_f	: Flare initiation flight velocity
h_a	: Initial altitude	α	: Angle of attack
h_f	: Flare initiation altitude	ρ	: Air density
m	: Total weight of the airplane	τ	: Flare time constant
R	: Turning radius	ϕ	: Roll angle
S	: Wing area	ψ	: Nose azimuth angle

1. Introduction

In recent years, the use of unmanned aerial vehicles (UAVs) has advanced, enabling applications such as services for monitoring agricultural land, surveying disaster-stricken areas, and transporting goods, and research and development exploring future possibilities in these areas is ongoing [3]. In particular, the use of fixed-wing UAVs is more advantageous than rotary-wing multicopters in the field of logistics and in disaster damage assessment due to their superior speed and longer flight range. However, fixed-wing UAVs that fly at high speeds require a long landing distance. This makes it impossible to land in forested or urban areas with high obstacles in the vicinity of the landing site. To address this problem, this study aims to reduce the horizontal distance required for landing by using both highly accurate turn path tracking and deceleration with turning descent technology.

Usually, in glide slope landings, airplanes follow a straight descent path at a constant speed before transitioning to the flare phase, in which the descent rate is reduced inversely proportional to its altitude, resulting in a small impact at touchdown. In conventional short-range landing technology, airplanes increase their angle of descent (glide slope angle) in the glide slope phase [4, 5]. In contrast, the proposed deceleration and turning descent technology enables airplanes to decelerate and descend while performing multiple turns along a predetermined circular trajectory. This method shortens the horizontal distance required for landing while simultaneously reducing flight speed at the time of touchdown. This leads to a shorter rollout distance, which in turn reduces the required runway distance.

As this technology is applied from the start of the landing phase to just before the flare phase, it is important to minimize the deviation from the target turning path. Therefore, a flight control system that enables continuous and highly accurate turning along a predetermined circular path is required. There are many papers on turning technology, including a study on saving space in half-circle turns [7] and a study on following complex paths with gentle curves [8]. However, no prior research has focused on achieving continuous turning along a predetermined circular path. To address this gap, the authors utilize their previously reported highly accurate turn path tracking technology for continuous turning to reduce the turning path deviation [9].

Secondly, in previous studies on deceleration and turning descent technology [6], the rate of descent during deceleration and turning descent was regarded as constant to simplify calculations. However, this assumption led to prolonged flight times from the start of landing to touchdown. Therefore, in this paper, the maximum instantaneous descent rate that can be realized is calculated in real time by using flight status data.

Finally, the present paper describes the results of a 6-DOF simulation conducted to validate the proposed deceleration and turning descent technology, followed by flight verification experiments using a small fixed-wing UAV to assess the accuracy of the turn path tracking technology.

2. Proposal of deceleration and turning descent technology

The main objective of the proposed deceleration and turning descent technology is to reduce the horizontal distance for landing, which will enable fixed-wing UAVs to land in small spaces where only multicopters would typically be able to land. The details of the landing flow are described below.

The landing profile using the deceleration and turning descent technology consists of four flight phases. The first phase is the horizontal turning phase. The purpose of this phase is to eliminate the initial path errors before entering the next deceleration and turning descent phase, so as to realize an accurate turning path. The second phase is the deceleration and turning descent phase. In this phase, the UAV descends by executing multiple turns along a circular trajectory with a constant turning radius while simultaneously decelerating its speed. The descent occurs at the maximum rate of descent and decelerates at a constant rate of acceleration. In the third and fourth phases, the UAV goes through the transition and flare phases, respectively, leading to touchdown. The transition phase is responsible for positioning the UAV on the runway and reducing the deep roll angle induced by turning to zero in preparation for the flare phase.

Deceleration and descent continue during the transition phase. Fig.1 shows an image of the landing flow described above.

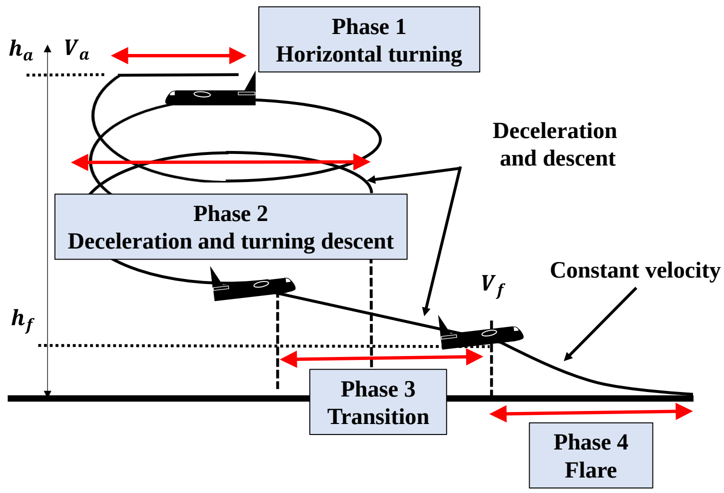

Fig.1 Landing flow of deceleration and turning descent technology.

3. Derivation of target values

For manned airplane, risky flight maneuvers such as deep rolls and low-speed flight close to stall conditions are generally avoided in consideration of safety. However, since this technology is specifically designed for UAVs, it is possible to set target values that make the best use of UAV performance.

In applying the deceleration and turning descent technology to UAVs, target values are set for three parameters: flight speed, turning radius, and descent rate. The policies and derivation methods for each of these parameters are described below.

3-1 Minimum flight speed

Flight speed is an important parameter that determines the distance the UAV will run after its touchdown.

This technology reduces the required runway distance by minimizing the flight speed at touchdown after deceleration during descent. The minimum flight speed at touchdown is determined up to and just before the stall limits of the UAV.

In general, the stall speed V_{stall} is derived using the stall angle of attack α_{stall}, which is a characteristic of the UAV's performance. Eq. (1) is a transformation of the equation for the longitudinal force acting on the UAV and is used to derive the stall speed V_{stall}.

$$V_{stall} = \sqrt{\frac{2mg}{\rho S C_{L\alpha} \alpha_{stall}}} \tag{1}$$

For safety, the minimum flight speed is defined as the stall speed V_{stall} derived in Eq. (1) with a margin of 30%, and this is set as the flight speed at the start of the flare phase V_f (Eq. (2)). Since the flight speed is kept constant during the flare phase, which is without deceleration, the minimum flight speed can be maintained for touchdown.

$$V_f = 1.3 V_{stall} \tag{2}$$

3-2 Minimum turning radius

The horizontal distance covered during deceleration and turning descent depends only on the turning radius, so minimizing the turning radius will result in a shorter horizontal distance. The minimum turning radius can be derived structurally by using the load carrying capacity of the target UAV [10]. However, in this case, the minimum turning radius R_{min} is derived from the maximum roll angle ϕ_{max} of the UAV.

First, the maximum roll angle ϕ_{max} of the UAV is derived. Eq. (3) is a transformation of the equation for the longitudinal force balance during turning, and is used to determine the maximum roll angle ϕ_{max}.

$$\phi_{max} = \cos^{-1}\left(\frac{2mg}{\rho S {V_f}^2 C_{L\alpha} \alpha_{stall}}\right) \tag{3}$$

Next, the minimum turning radius R_{min} is calculated by using Eq. (4), which is derived from the equilibrium equations for longitudinal and lateral forces during the turning. Substituting the maximum roll angle ϕ_{max} derived in Eq. (3) into Eq. (4), the minimum turning radius R_{min} can be derived.

$$R_{min} = \frac{V^2}{\tan(\phi_{max}) g} \tag{4}$$

3-3 Maximum rate of descent

The descent rate determines the flight time required for landing. Since the proposed technology reduces the UAV's speed greatly, the descent rate must be maximized to compensate for the potential increase in flight time. We proposed the following procedure to determine the maximum rate of descent.

First, by using the relationship between the forces in the direction of flight, the maximum rate of descent can be derived as shown in Eq. (5) with the flight speed as a variable. Here, the angle of attack used to calculate the drag force D in Eq. (5) is derived from the lateral equilibrium equation in order to maintain stability during turning. T_{min} is the minimum thrust of the UAV.

$$dh/dt = V \cdot \sin^{-1} \frac{D - T_{min}}{mg} \tag{5}$$

Next, the descent altitude can be calculated by integrating the rate of descent up to the flare start time, as shown in Eq. (6). Here h_a is the initial altitude of the landing and h_f is the initiation altitude of the flare. In general, the flare initiation altitude is derived using Eq. (7).

$$\int_0^{t_f} {dh}/{dt}(V) \quad dt = h_a - h_f \tag{6}$$

$$h_f = {dh}/{dt} \cdot \tau \tag{7}$$

Finally, Eq. (8) is defined to derive the flight speed using the acceleration a during deceleration and turning descent.

$$V(t) = at + V_a \tag{8}$$

Substituting Eq. (5) and Eq. (8) into Eq. (6) and solving the definite integral, we obtain the flight time required for deceleration and descent (flare start time t_f), the flight acceleration a, and maximum rate of descent.

4. Target UAV and path

4-1 Target UAV

The target UAV for this study is a low-wing glow fuel-powered model UAV, as shown in **Fig.2**. **Table 1** lists the UAV specifications.

Fig.2 Photograph of UAV.

Table 1 UAV specifications.

Total weight	m	5.5 kg
Wing area	S	0.65 m^2
Aspect ratio	AR	6.54
Wing efficiency	e	0.6
Lift curve slope	$C_{L\alpha}$	4.355 1/rad
Parasite drag coefficient	C_{D0}	−0.0485
Minimum thrust	T_{min}	3 N

4-2 Derived target path

Using UAV specifications listed in **Table 1** and initial conditions from **Table 2**, the target values are calculated following the procedures described in Section 3.

Table 2　Initial conditions.

Initial altitude	h_0	100 m
Initial flight velocity	V_0	25 m/s
Transition phase duration		5 s
Flare time constant	τ	2.5 s

The computed target values are shown in Fig.3 together with the landing profile. Given the runway distance limitations for the flight verification experiment, the UAV initiates its turn from the opposite side of the landing direction, and after turning n.5 times (n = real number), it aligns its nose with the landing direction on the runway and lands.

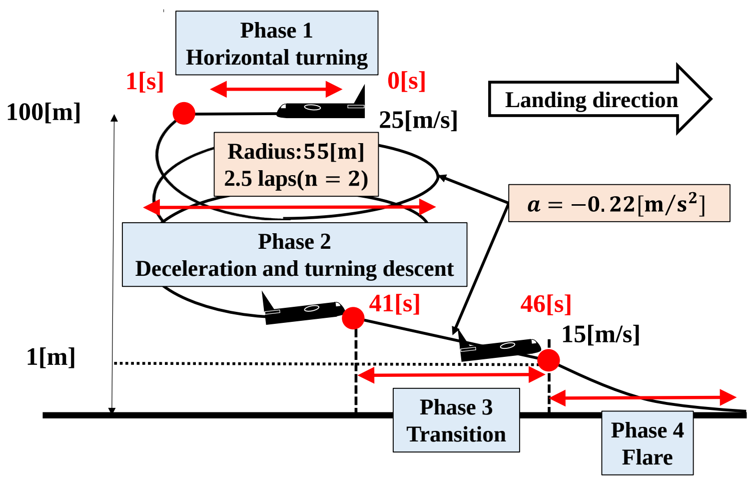

Fig.3　Derived target values and landing profile.

The minimum turning radius of the target UAV was calculated to be 55 m. The UAV performs a 2.5-lap deceleration and turning descent trajectory with a turning radius of 55 m. After maintaining a horizontal turning phase for 1 second, it transitions into the deceleration and turning descent phase, followed by a 5-second transition phase, reaching the flare phase at 46 seconds. During the transition from the deceleration phase to the flare phase, the UAV experiences an acceleration of $-0.2\ m/s^2$. At the start of the flare phase, the UAV decelerates to 15 m/s, its minimum flight speed, and descends from an altitude of 100 m to 1 m. The time histories of the maximum rate of descent and the altitude are shown in Figs.4 and 5, respectively. The time history of the maximum rate of descent is shown in Fig.4. Additionally, Fig.5 shows the time history of the altitude calculated by the maximum rate of descent. The time history of the altitude is input as a command to the simulation to be performed later.

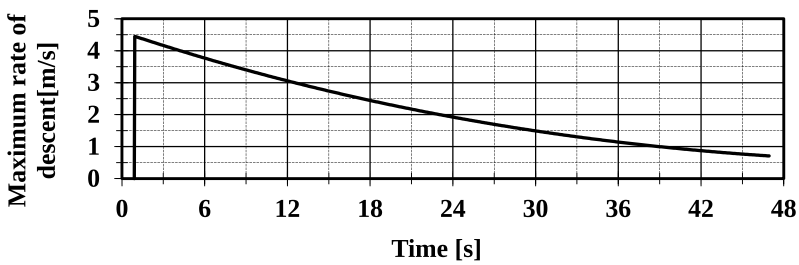

Fig.4　Time history of the maximum rate of descent.

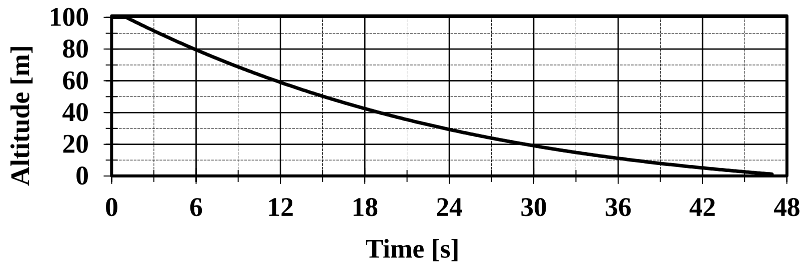

Fig.5 Time history of altitude.

5. Control systems

In order to realize the proposed deceleration and turning descent flight, the following three systems were designed: speed control, altitude control, and turning path tracking control.

(a) Speed control system

The airspeed is controlled by the throttle. Airspeed is measured using a Pitot tube mounted on the UAV, and the airspeed command is given to decelerate the airspeed at a constant rate, as calculated in Section 4. Deviations from the command are processed through a PID controller to generate the engine throttle command.

(b) Altitude control system

The altitude is controlled by the pitch angle. Sensors installed on the airplane measure the altitude, and the time history of the altitude calculated from the maximum rate of descent shown in Fig.5 is used as input for the descent command. Deviations from the command are processed through a PID controller to generate the pitch angle command.

(c) Turning path tracking control system

This control system is indispensable to realize the proposed technology. It enables the UAV to track the target turning path by focusing on the turning radius deviation and nose azimuth angle. The azimuth command ψ_{cmd} generated from the turning radius deviation and the ideal azimuth angle ψ_{tan} calculated from the current position and the turning center of the UAV are added together and input to the nose azimuth angle control system. Then, from the deviation between this added command and the current nose azimuth angle ψ, a roll angle command ϕ_{cmd} is generated and input to the roll angle control system (Fig.6).

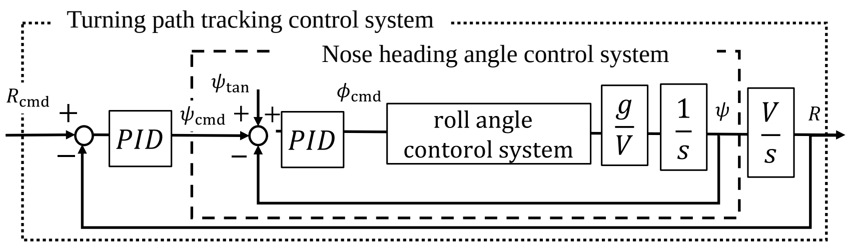

Fig.6 Turning path tracking control system.

6. Simulation

6-DOF simulations using Matlab/Simulink were performed to confirm the effectiveness of the proposed technology.

6-1 Simulation conditions

The simulation consists of a 50-second linear path-following controlled flight at a speed of 25 m/s, followed by the landing profile shown in Fig.3. Initial conditions are summarized in Table 2. Sensor noise, as observed in actual flight experiments, was added in the simulation, with standard deviations as summarized in Table 3. Also, the feedback rate for simulation is 40 ms.

Table 3　Standard deviation of sensor noise.

Attitude angle	0.5 deg.
X, Y direction	3 m
Altitude	0.2 m
Velocity	0.17 m/s

6-2 Target performance

For the simulation, target performance parameters were defined for touchdown. Table 4 lists the lateral position deviation at touchdown, determined from the runway width of 6 m, and the rate of descent at touchdown, based on the target UAV's leg structure.

Table 4　Target performance at touchdown.

Lateral position deviation	±3 m
Rate of descent	1 m/s

6-3 Simulation results

Fig.7 shows the flight path, velocity, altitude, and attitude angles obtained from the simulations. The time histories show results after 50 seconds into the horizontal turning phase. Fig.7(a) and (b) show the flight trajectories, demonstrating that the UAV followed the target path for a turning descent of 2.5 laps. Fig.7(c) and (d) respectively show the time histories of velocity and altitude. It can be seen that both are following the command, decelerating and descending as expected. Fig.7(e) shows the time history of the turning radius. At the start of the turn, the radius overshoots due to a delay in the control system, but eventually converges to the command. Fig.7(f) and (g) show the pitch and roll angles, respectively. It can be seen that both angles are following the command.

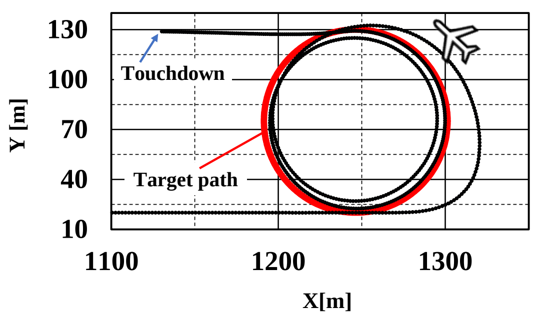

Fig.7(a)　Flight path (X-Y).

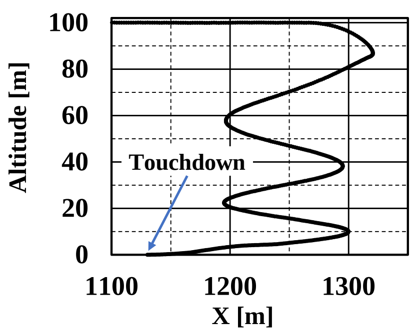

Fig.7(b)　Flight path (X-Altitude).

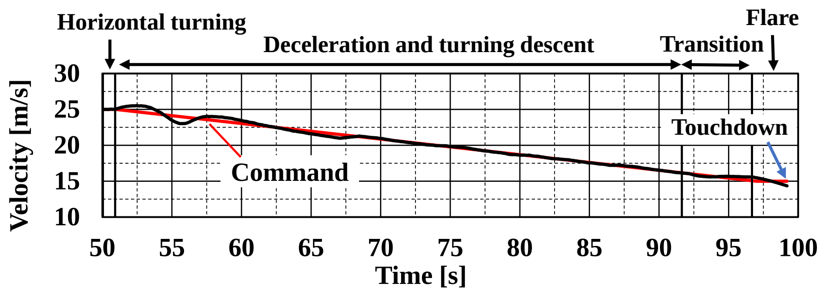

Fig.7(c)　Time history of velocity.

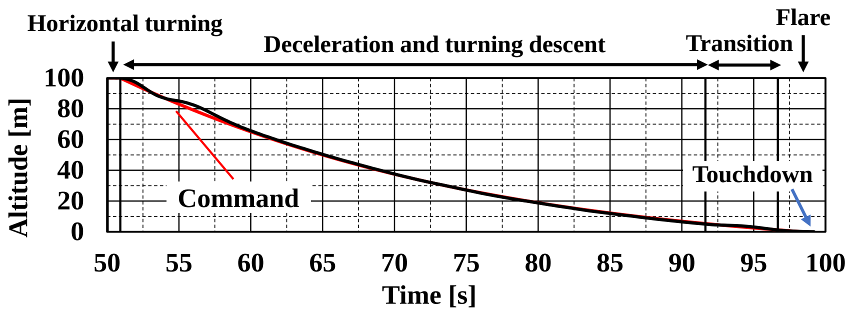

Fig.7(d)　Time history of altitude.

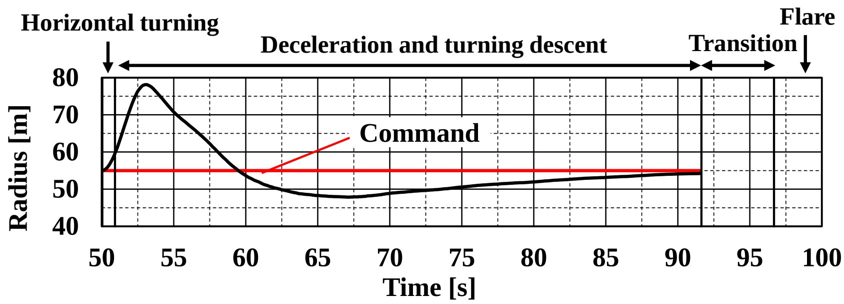

Fig.7(e)　Time history of turning radius.

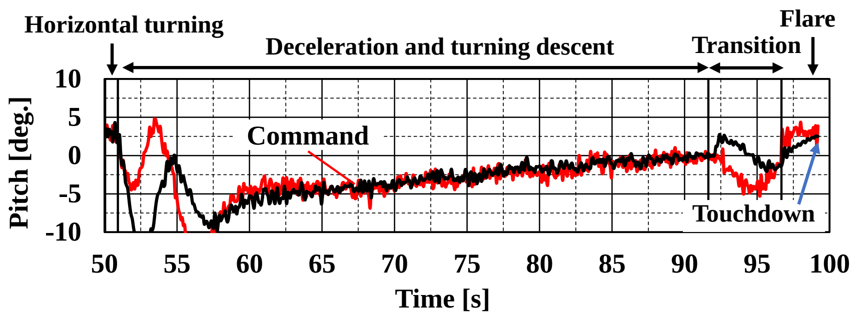

Fig.7(f)　Time history of pitch angle.

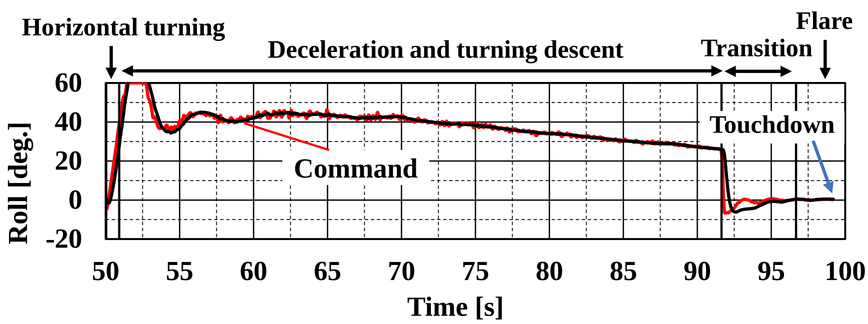

Fig.7(g)　Time history of roll angle.

Next, the performance at touchdown is summarized in **Table 5**. These results were confirmed to be within the target performance parameters.

Table 5 Simulated performance at touchdown.

Lateral position deviation	1.1 m
Rate of descent	0.12 m/s

6-4 Discussion of results

The total landing distance is evaluated for the simulation results using this technology compared to the conventional technology [4]. The landing distance is defined as the horizontal linear distance covered by the plane as it descends from an altitude of 100 m to touchdown. However, for the distance from touchdown to stop (roll-out distance L_o), an approximate formula Eq. (9) [11] is used.

$$L_o = \frac{1}{2g}\frac{V^2}{D/W} \tag{9}$$

By applying the conventional technology to the target UAV in this study, the maximum glide slope angle is calculated to be 15 deg. The UAV descends at a constant flight speed, and after a flare phase, it touches down at a horizontal distance of 530 m. The UAV then glides over the runway for a distance of 30 m, stopping at 560 m.

In contrast, in the simulation using the proposed technology, the UAV touches down at a horizontal distance of 190 m. Then, the UAV stops after a distance of 10 m, which is much shorter than the runway distance required by the conventional technology, because the speed of the UAV is reduced to 15 m/s. Therefore, the total landing distance is reduced to 200 m, representing a 64% reduction in horizontal distance.

7. Flight verification

To validate the proposed technology, flight verification experiments were conducted in stages using the fixed-wing UAV shown in **Fig.2**. The flight experiment was carried out at the Shiraoi Gliding Port in Hokkaido, Japan. The weather on the experiment day was favorable, with a temperature of about 15 degrees Celsius and a steady wind of 2 to 3 m/s. The feedback rate was 40 ms, the same as in the simulations. First, the continuous level turning flight experiment was carried out, which involves a highly accurate turn path tracking technology. For the target UAV, the minimum turning radius was set to 55 m. The shorter the turning radius is, the bigger the roll angle during the turn. In the flight experiment conducted in a previous study [9], the altitude of the UAV dropped by almost 7 m for a turning radius of 70 m.

Therefore, in the present paper, flight experiments were carried out sequentially with a turning radius of 85 m, 70 m, and 55 m, in that order, and the effect of changes in the turning radius on the altitude were investigated.

In all cases, the UAV was set to fly 3.5 laps of continuous circles, and was controlled to maintain a constant altitude at the beginning of the experiment and a constant airspeed of 25 m/s.

7-1 Target performance for flight verification experiments

The purpose of this test is to confirm the convergence of the highly accurate turn path tracking technology applied to the deceleration and turning descent phase. Therefore, the turning radius deviation was set and evaluated as the target performance after convergence. The target performance of the converged deviation was set within 9 m, which takes into account the positional error of 3 m measured by the sensor and control errors. For the experiment, only the average deviation after the second lap was evaluated, because the first lap of the continuous turning expands the turning path due to the delayed response of the roll.

7-2 Results of flight verification experiments

The flight paths and time histories of the turning radii of 85 m, 70 m, and 55 m are shown in Figs.8 to 10, respectively. The black line in the flight path diagram represents the circular path of the target.

Fig.8(a) Fight path (85 m).

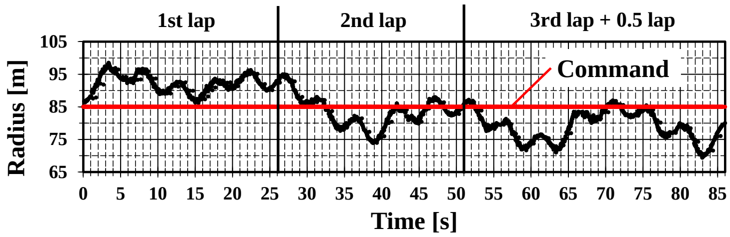

Fig.8(b) Time history of turning radius (85 m).

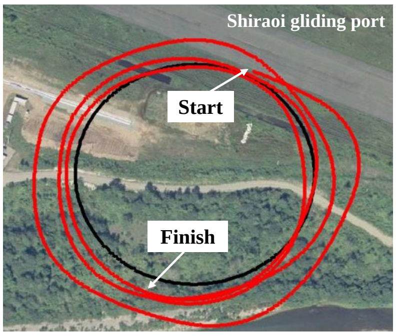

Fig.9(a) Fight path (70 m).

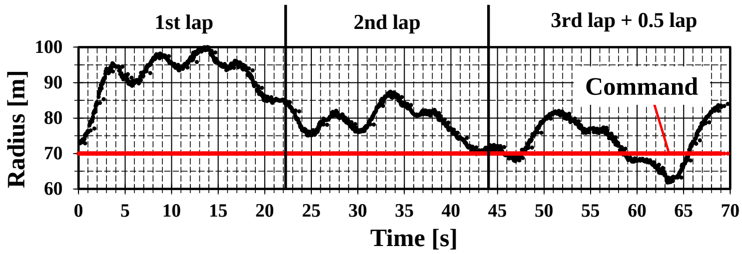

Fig.9(b) Time history of turning radius (70 m).

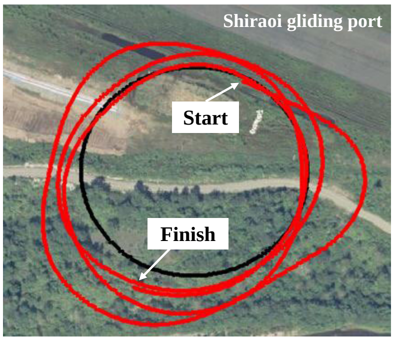

Fig.10(a) Fight path (55 m).

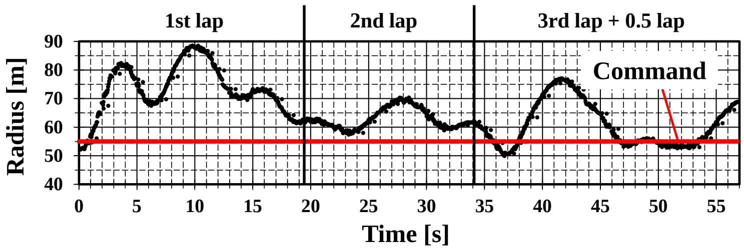

Fig.10(b) Time history of turning radius (55 m).

All patterns show continuous turning along a path that is generally in line with the target path. However, compared to the time history of the turning radius in the simulation (Fig.7(e)), in the actual flight experiment, the turning radius is oscillating. This is considered to be due to the 2 to 3 m/s wind disturbance present in the flight verification experiment environment. The simulations described in Section 6 did not take wind disturbance into account, so no oscillations were observed. On the other hand, in a previous study [9], a horizontal continuous turning simulation under the condition of 3 m/s wind disturbance was conducted that found oscillations of about 3.6 m for a command with a turning radius of 70 m. Therefore, the oscillations observed in the turning radius in this experiment are judged to be acceptable.

The experiments were conducted multiple times to confirm the reproducibility of the test, and it was found that with wind disturbance of more than 5 m/s, the turning radius showed greater oscillations and tended to diverge.

Next, we consider the convergence. As expected for all patterns, the first lap was affected by the delay of the control system and the response delay of the roll, and the radius deviation tended to increase. The average deviation excluding the first lap is summarized in Table 6. In all cases, the radius deviation converged to within 9 m of the target performance. In addition, it was found that even with a minimum turning radius of 55 m for the target UAV, the target performance could be satisfied and continuous turning was possible. From these results, the validity of the highly accurate turn path tracking technology was confirmed, and it became clear that the proposed technology can actually be applied to the deceleration and turning descent phase.

Table 6　Convergence values for each turning radius.

Target turning radius	Average deviation excluding the first lap
85 m	5.2 m
70 m	7.0 m
55 m	7.2 m

Next, the effect of varying turning radius on altitude is discussed. Table 7 summarizes the deviation from the altitude command after 3.5 laps for each turning radius we investigated. As initially predicted, it became clear that reducing the turning radius to 55 m resulted in an increase in the altitude deviation. However, the same PID parameters of the altitude control system are applied for all turning radii. It is expected that the increase in the altitude deviation can be mitigated by redesigning the controller parameters to improve the response when the UAV must execute turns with a smaller radius.

Table 7　Deviation from the altitude command after 3.5 laps for each turning radius.

Target turning radius	Deviation from the altitude command after 3.5 laps
85 m	−5.6 m
70 m	−5.4 m
55 m	−7.2 m

8. Conclusion

In this paper, a new UAV landing technology that incorporates a deceleration and turning descent during the glide slope phase is proposed. This approach is aimed at reducing the horizontal distance required to land fixed-wing UAVs. A 6-DOF simulation was carried out using this technology to investigate its validity. It was confirmed that the horizontal landing distance could be reduced by up to 64% compared to the conventional short-distance landing technology, which uses a high glide slope angle.

Flight verification experiments were also conducted as a first step to evaluate the highly accurate turn path tracking technology. Results of the flight verification experiment showed that even with a minimum turning radius of 55 m, the target UAV was capable of continuous turning, with the target performance metrics satisfied. Our future goal is to establish this technology through actual flight verification in which the UAV performs both highly accurate continuous turning, deceleration, and descent simultaneously.

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飛行中ワイヤレス電力伝送に向けたドローン飛行制御システムの開発

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本研究では，飛行中ドローンへのワイヤレス電力伝送の実現を目的として，充電時を想定した高精度なドローン飛行制御システムを開発した。具体的には，カメラによるARマーカー位置推定システムとマイクロ波電力伝送を模擬した光源位置推定システムを開発し，それぞれの位置推定システムを用いてドローン制御実験を実施した。ARマーカー位置推定システムは遅延が大きくドローンの傾き補正によって精度が低下するのに対し，光源位置推定システムは高精度かつ低遅延で位置が推定可能である。一方で，ARマーカーを用いる場合はカメラの画角に応じて比較的広い範囲で制御可能であるのに対し，光源位置推定システムは制御可能範囲がビームの照射範囲に限定されることが明らかとなった。

Keywords: 光源位置推定，信号強度，ARマーカー，リアルタイム制御，ドローン制御，ワイヤレス電力伝送

Development of Drone Flight Control System for In-flight Wireless Power Transmission

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In this study, we developed a high-precision drone flight control system to enable wireless power transmission to drones in-flight, particularly during charging operations. Specifically, an AR marker-based position estimation system using a camera and a light source position estimation system simulating microwave power transmission were developed. We conducted drone control experiments with both systems to evaluate their accuracy, latency and operation range. The findings demonstrated significant differences between the two systems. The light source position estimation system achieved high accuracy and low latency, making it suitable for applications requiring high-prediction position estimation. However, its controllable range was limited to the beam's illumination area. In contrast, the AR marker-based system allowed for control over a comparatively broader range based on the camera's field of view, despite experiencing high latency and reduced accuracy caused by drone tilt corrections.

Keywords: Light source position estimation, Signal strength, AR Marker, Real-time control, Drone control, Wireless power transmission

1. はじめに

近年，ドローンは物流，監視，災害救助など多様な分野で活用されている。しかし，電動式ドローンにおけるバッテリー持続時間の制約は，依然として大きな課題である。この問題を解決する手段として，ワ

イヤレス電力伝送技術の研究が進められている [1, 2]。特に，飛行中のドローンに向けてマイクロ波ビームの指向性を制御するための機構（電子的または機械的）を必要とする場合，非常に高コストとなる。そのため，直上に放射したマイクロ波ビームに対してドローン自身を移動・制御することを想定した研究も進められている [3, 4]。このシステムにおいては，ドローンが給電スポットの上空で高精度にホバリングするためのリアルタイム制御が不可欠である。

給電スポットの上空にドローンをホバリング制御する方法として 3 つ（GPS，カメラ，電磁波）が考えられる。まず，RTK-GPS（Real-Time Kinematic GPS）は GNSS 値を利用することでセンチメートル単位の位置情報を提供可能にする [5]。しかし，この方法は安定したネットワーク接続を必要とし，特に複雑で高度なシステムにより冗長性を確保しなければ，不安定なネットワークにより，予期せぬ遅延が発生し，正確なホバリングが不可能となる。そのため，任意の場所から給電スポット付近に近づく際に有効と考えられるが，ホバリングの安定性には課題が残る。次に，送電アンテナに AR マーカーを装荷し，ドローンに搭載したカメラを用いて上空から撮影し，画像処理によって相対位置を検出する方法が考えられる [6, 7]。この手法は GPS と比較してさらに高い精度が期待される一方，ドローンに搭載可能な性能のマイクロコンピュータを使用した画像処理は計算リソースの制約により，遅延時間が比較的大きいことが予想される。最後に，ワイヤレス電力伝送に用いるマイクロ波ビームを検知し，その位置を推定する方法が考えられる [8]。この手法は，あらかじめビームの放射特性を知っておく必要があるものの，計算リソースが小さく，信号対雑音比が高いため，高精度かつリアルタイムな制御が可能である。ビームが照射される狭い範囲においては特に有効な方法であると言える。

本研究では，GPS に依存しない制御方法に焦点を当て，AR マーカーを利用した制御方法とマイクロ波ビームを模擬した光を利用した制御方法 [9-12] による制御精度を比較するホバリング制御実験を実施した。本実験では，両者ともドローンに搭載した Raspberry Pi 5 を用いて位置推定および制御を行うことで，地上の無線通信による制御遅延を排除した。

2. ドローン飛行制御に向けた位置推定システム

本研究では，AR マーカーを利用した制御方法（以下「AR マーカー位置推定システム」）と光を利用した制御方法（以下「光源位置推定システム」）を比較し，ドローン飛行制御精度を評価する。

2-1 AR マーカー位置推定システム

2-1-1 マーカーの選定

カメラ認識により情報を取得可能なマーカーには様々な種類が存在し，用途に応じて適切な選択が必要である。本研究では，カメラ画角内における単一マーカーの位置を高精度かつ低遅延で特定することを目的としている。そのため，低解像度にして計算リソースの負担を抑えたとしても，高い検出性能を実現可能なマーカーとして，6×6 ビットのバイナリパターンを持つ AR マーカーを採用した。この AR マーカーは，白と黒の正方形で構成されるグリッド構造を持ち，低解像度の画像においてもコントラストのある領域として認識されやすい特徴を有する。また，6×6 ビットのパターンは，誤認識を防ぐために十分な情報量を持ちつつ，低解像度での認識を可能にする適切なセルサイズを確保できる。これにより，計算負荷を抑えながらも，安定したマーカー検出を実現できる [6, 7]。

検出および位置推定には，**図 1** に示す ArUco ライブラリの AR マーカー（ID＝1）を利用した。このライブラリは，マーカーのリアルタイム認識において高い信頼性を誇るオープンソースソフトウェアである。特に，カメラ校正パラメータ（内部パラメータおよび歪み係数）とマーカーサイズを事前に設定することで，カメラ画像上のピクセル座標から実空間の三次元座標への変換を高精度に行うことができる。なお，パターンの違いによる性能差はないため，異なる ID のマーカーを用いることもできる。

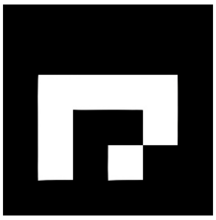

図 1　6×6 ビット AR マーカー（ID＝1）

2-1-2　カメラの選定

本研究では，Raspberry Pi Camera Module 3 を採用した。選定理由は，軽量かつコンパクトな設計でドローン搭載に適していること，必要以上の高解像度は計算リソースを大きくするため不要であること，さらに Raspberry Pi 5 との高い互換性によりシステム連携が容易であることである。ドローンとカメラおよび AR マーカーの位置関係を**図 2** に示す。ドローンを原点とし，AR マーカー (x, y, z) を z 軸負の方向に向けて設置する。また，カメラはドローン下部に z 軸正の方向に取り付けることで，AR マーカーを視認できるようにしている。

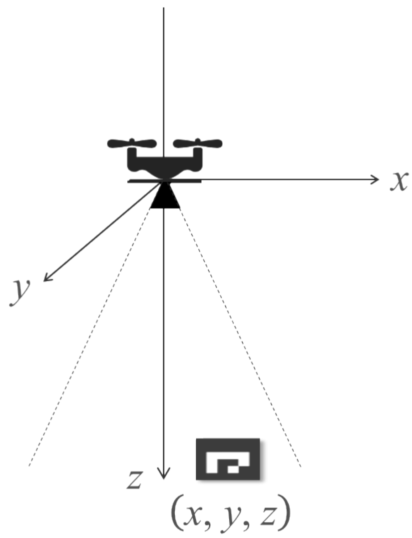

図 2　AR マーカーとドローンの位置関係

2-1-3　カメラの傾きによる推定位置の補正

ドローンがロール（横方向の傾き）およびピッチ（前後方向の傾き）を持つ場合，その機体に固定されたカメラも同様に傾く。この結果，AR マーカーの位置がカメラ座標系において傾きを反映した形で計測されるため，**図 2** の座標系において正確な位置推定ができない。そこで本研究では，カメラの傾きを補正し，ドローンおよびカメラが鉛直状態であったと仮定した場合の AR マーカー位置を推定する手法を採用した。この手法では，ドローンの姿勢角（ロール角およびピッチ角）をリアルタイムで取得し，その情報を基に回転行列を構築して位置補正を行う。具体的には，カメラの傾きを示す回転行列 $\boldsymbol{R}$ を構築し，カメラ座標系で計測された AR マーカーの位置ベクトル $\boldsymbol{P}_{\mathrm{observed}}$，ドローンおよびカメラが傾いていなかった場合に対応する補正後の位置ベクトル $\boldsymbol{P}_{\mathrm{corrected}}$ を用いて補正を行った。回転行列 $\boldsymbol{R}$ は以下のように計算される。

$$\boldsymbol{R} = \boldsymbol{R}_{\mathrm{roll}} \cdot \boldsymbol{R}_{\mathrm{pitch}} \, . \tag{1}$$

ロール角 φ に基づく回転行列 $\boldsymbol{R}_{\mathrm{roll}}$ およびピッチ角 θ に基づく回転行列 $\boldsymbol{R}_{\mathrm{pitch}}$ は以下のように表される。

$$\boldsymbol{R}_{\text{roll}} = \begin{bmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{bmatrix}, \quad \boldsymbol{R}_{\text{pitch}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}. \tag{2}$$

以下の変換式によって補正を行った。

$$\boldsymbol{P}_{\text{corrected}} = \boldsymbol{R}^{-1} \cdot \boldsymbol{P}_{\text{observed}} . \tag{3}$$

2–2　光源位置推定システム

2–2–1　光源の設定

本研究では飛行中ドローンに対する高精度な制御を目的としているため，光強度に大きな差が生じる指向半値角 2.5° という狭い放射角の光源（スタンレー株式会社 LLM0854A/LIGHTING EQU50:5000K）を使用した。ドローンと光源の位置関係を**図 3** に示す。ドローンを原点とし，光源位置 (x, y, z)，受信点位置 (x_i, y_i, z_i)，光源の照射方向 $\boldsymbol{L} = (0, 0, -1)$ とする。また，光源からある受信点に向かう光の伝播ベクトルを $\boldsymbol{D}$ とする。

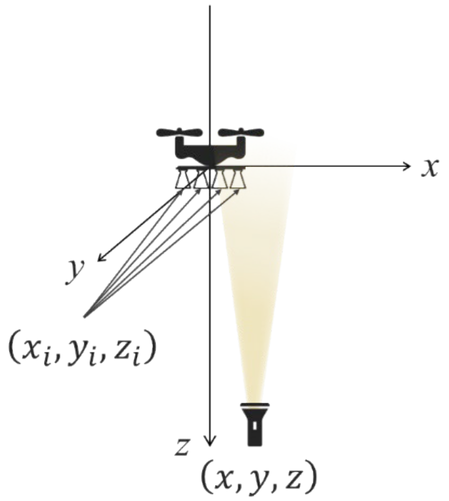

図 3　光源とドローンの位置関係

2–2–2　光強度分布のモデル化

受信点を用いて環境光が計測上無視できる空間で光強度を計測し，関数フィッティングを用いて光の強度分布 $\hat{I}$ [mA] を数学的なモデルとして表現する。指向性 G_r はフィッティング係数 σ を持つ角度 θ のガウス関数を用いて**図 4** に示すようにフィッティングを行った。その結果，$\sigma = 0.0156$ となった。距離減衰 I_d [mA] はフィッティング係数 a, b を持つ距離 d[m] の逆二乗の関数を用いて**図 5** に示すようにフィッティングを行った。その結果，$a = 3.484, b = 0$ となった。b は環境光の影響を受ける定数項である。

$$\hat{I} = G_r \cdot I_d = \left(\frac{a}{d^2} + b\right) \cdot \exp\left(-\frac{\theta^2}{2\sigma^2}\right). \tag{4}$$

d, θ は以下のように表される。

$$d = \sqrt{(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2} . \tag{5}$$

$$\cos\theta = \frac{\boldsymbol{D} \cdot \boldsymbol{L}}{|\boldsymbol{D}||\boldsymbol{L}|}. \tag{6}$$

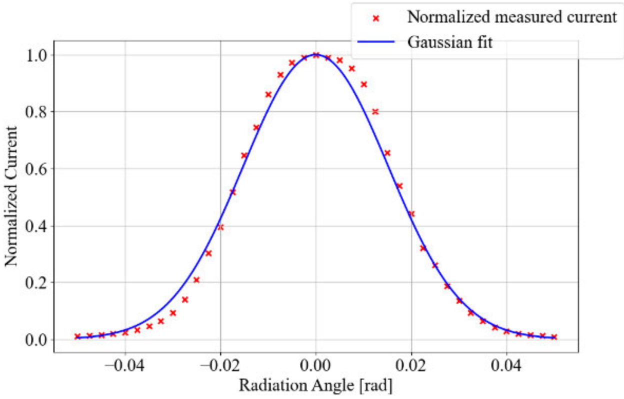

図 4　光強度測定とフィッティング（指向性）

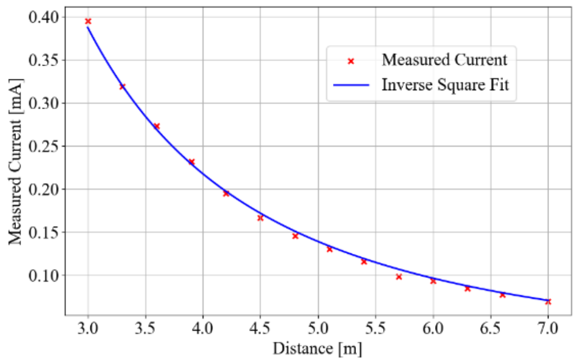

図 5　光強度測定とフィッティング（距離減衰）

2–2–3　誤差関数の構築

受信された光強度 I_i [mA] と理論上の光強度 $\hat{I}\,(x, y, z)$ の誤差を考慮した誤差関数 $f\,(x, y, z)$ を式 (7) のように定義する。この式は，各受信点 i から得られた I_i と $\hat{I}$ の差の二乗和を表している。誤差関数が最小となる位置が，最も適切な光源位置であると推定される。

$$f(x,y,z) = \sum_{i=1}^{N} \left(I_i - \hat{I}\right)^2 . \tag{7}$$

2–2–4　誤差関数の最適化

最急降下法を用いて，誤差関数を最小化するパラメータ（光源位置）を反復的に調整し，最適解を見つける。具体的には，現在の位置から誤差関数 $\nabla f\,(x_k, y_k, z_k)$ の勾配ベクトル $\nabla f\,(x_k, y_k, z_k)$ に従ってステップサイズ $\alpha_x, \alpha_y, \alpha_z$ を移動させることで誤差関数の値を減少させる。この式を (8) に示す。

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \\ z_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} - \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} \nabla f(x_k, y_k, z_k) . \tag{8}$$

2–2–5　受光基板

今回開発する受光基板は**図 6** に示すように，受信点は格子状に 9 個配置し，各受信点の間隔は 7 cm とした。これは，モーター間距離が 50 cm のドローンに搭載可能なサイズであり，推定精度，推定速度が高くなることを考慮したものである。光強度検出素子としてはフォトダイオードおよびフォトトランジスタが代表的であるが，本研究では応答速度の観点からフォトダイオード（Hamamatsu Photonics K.K.:S6775）を選択した。一般に，2–2–3 の誤差関数では，受信側の指向性を考慮する必要がある。しかし，本研究では，光がフォトダイオードに対して傾斜する場合であっても，その指向性の影響が実験条件下で無視できる範囲に留まることを確認した。そのため，本実験では受信側の指向性を考慮しないものとする。各フォトダイオードの回路図を**図 7**，開発した受光基板を**図 8** に示す。5 V の逆バイアス電圧を印加し，フォトダイオードが生成する光電流を電圧 V_{out} に変換するために最大抵抗値 20 kΩ の可変抵抗を用いて 10 kΩ 程度で使用する。これにより，キャリブレーションが可能となる。変換された電圧信号は，アナログ–ディジタル（AD）コンバータを経由して Raspberry Pi 5 に入力される。Raspberry Pi 5 上で実行されるアルゴリズムにより，光源位置の推定を行うことでドローンのスタンドアロン，低遅延制御が可能となる。

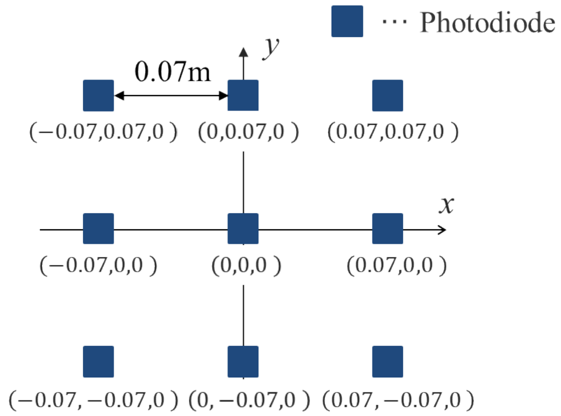

図 6　受光点配置

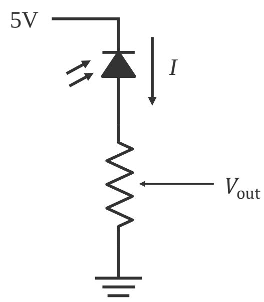

図 7　フォトダイオード回路

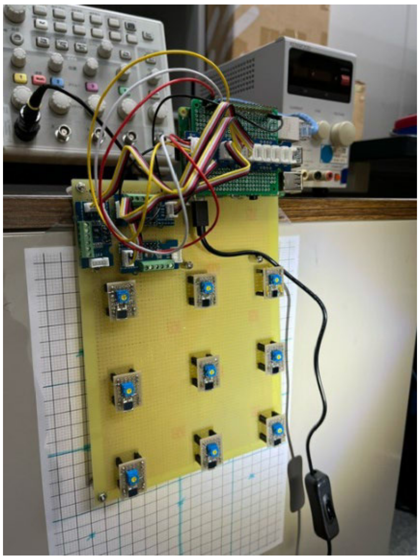

図 8　フォトダイオードアレイ基板

3.　飛行制御実験

今回の飛行制御実験には，**図 9** に示す Holybro PX4 Development Kit-X500 v2 を使用した。このドローンにはフライトコントローラーとして Pixhawk 6X，制御ソフトウェアとして ArduPilot を採用している。制御信号は Raspberry Pi 5 から Pixhawk 6X に対して UART を使用して送信する構成とした。本研究では，それぞれの制御方法の性能を評価するため，GPS を用いた位置制御を行わず，高度維持モードを使用した。このモードはドローンの高度を一定に維持する一方で，ホバリングモードとは異なり，ドリフト（水平移動）を補正しない。そのため，制御を行わない場合このドローンはモーター等のばらつきにより任意の方向に約 1.5 m/s の速度でドリフトする。実験の課題は，このドリフトに対して，各制御アルゴリズムがどの程度有効に機能するかを評価することである。

3-1　制御遅延時間の比較

制御遅延は，制御に用いるデータの処理時間による「情報遅延」と，制御の実行間隔による「制御周期遅延」の 2 種類に分類できる。本研究では，AR マーカー位置推定システムと光源位置推定システムのそれぞれにおける制御遅延時間を Raspberry Pi 5 を使用して測定した。その結果を**図 10**，**11** に示す。測定では，位置推定に必要な電圧値および画像データの取得をノイズ軽減と遅延削減のバランスを考慮して 3 回行い，その平均値を用いた。また，AR マーカー位置推定システムでは，計算リソースとマーカー認識

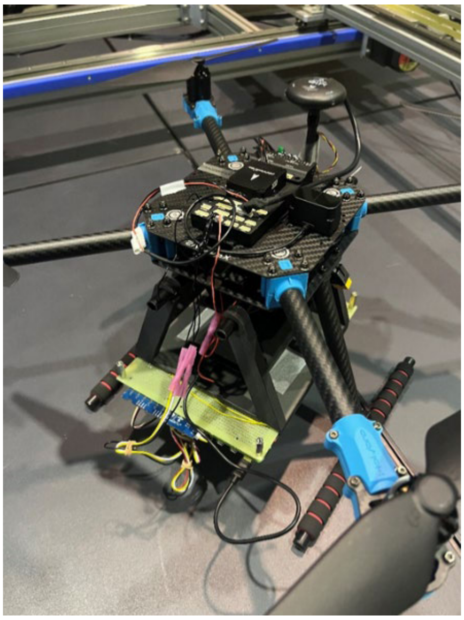

図 9　Holybro：PX4 Development Kit - X500 v2

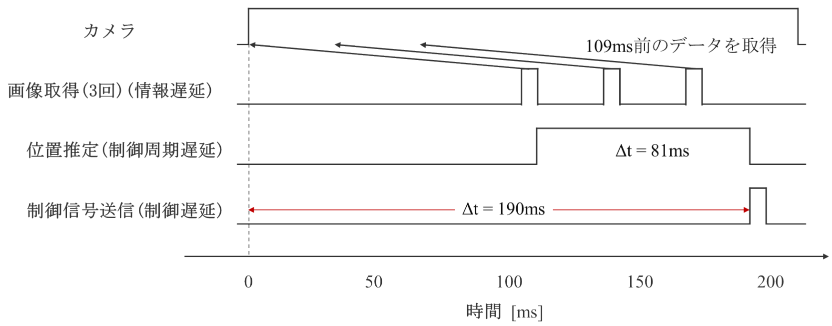

図 10　AR マーカー位置推定システムのタイムチャート

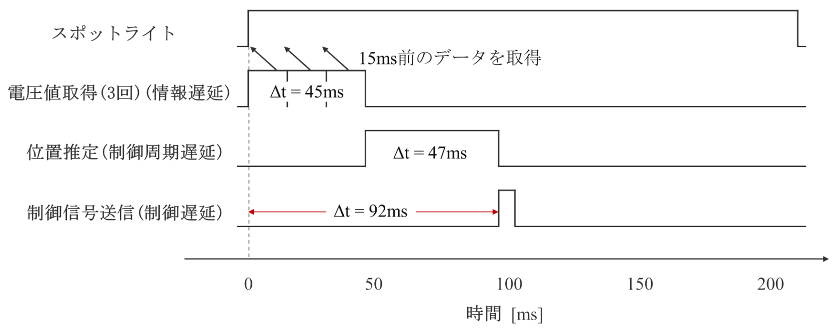

図 11　光源位置推定システムのタイムチャート

率のバランスを考慮し，画像の解像度を 640×480 px に設定した。一方，光源位置推定システムでは，光を検知可能範囲内で十分な精度が得られるよう，最急降下法の試行回数を 10 回に設定した。測定結果から，AR マーカー位置推定システムと光源位置推定システムの制御遅延時間を比較した結果，光源位置推定システムは情報遅延および制御周期遅延の両面で AR マーカー位置推定システムよりも小さい値を示した。

情報遅延は，AR マーカー位置推定システムは 109 ms，光源位置推定システムは 15 ms という結果になった。AR マーカー位置推定システムではカメラからの画像取得，光源位置推定システムでは光センサーか

らの電圧値取得が情報遅延の主な要因である。電圧値のデータは画像と比較してデータ量が小さいため，短時間で処理が可能であり，情報遅延が小さくなったと考えられる。

制御周期遅延について，ARマーカー位置推定システムは81 msであり，光源位置推定システムは47 msという結果になった。ARマーカー位置推定システムでは認識アルゴリズムによる画像処理，光源位置推定システムでは最急降下法による最適化が制御周期遅延の主な要因である。ARマーカー位置推定システムでは画像取得後，認識アルゴリズムを用いて位置推定を行い，これを3回繰り返して平均化する。一方，光源位置推定システムでは3回のデータ取得および平均化後，最急降下法を用いて位置推定を行う。そのため，光源位置推定システムの方が位置推定のプロセス回数が少なく，制御周期遅延が小さくなったと考えられる。

3-2　飛行制御実験結果

ARマーカー位置推定システムと光源位置推定システムについて，高度4 mにおいてARマーカーおよび光源上空にホバリングさせる飛行制御実験を行った。まず，ARマーカー位置推定システムにおいて最適化したPIDゲインを光源位置推定システムに適用した場合，光の検知範囲がカメラの視野角と比較して小さいため，ドリフトに対して制御量が不足し光の検知範囲を外れる結果となった。一方で，光源位置推定システムにおいて最適化したPIDゲインをARマーカー位置推定システムに適用した場合，カメラの視野角が光の検知範囲と比較して大きいため，速度が過大になりARマーカーが検知できなくなる結果となった。以上から，それぞれ最適なPIDゲインを設定した。

ドローンが高速で動く場合，カメラで取得する映像にブレが発生し，ARマーカーの認識が困難となる。この問題に対し，シャッタースピードを高速化することで映像のブレを抑制可能だが，光の取り込み量が減少し画面が暗くなる。画面が暗くなりすぎると，ARマーカーを取得できなくなるため，今回はブレ抑制と光量のバランスを考慮してシャッタースピードを1 μsに設定した。また，ARマーカーの一辺のサイズは安定した認識が可能な30 cmとした。

各システムで推定された位置情報を基にドローンの軌跡を**図12**，**13**にプロットした。その結果，光源位置推定システムはより高精度に光源上空付近をホバリング可能であることが確認された。この結果は，情報遅延および制御周期遅延がより小さいことで応答性が優れていることが要因と考えられる。一方，AR

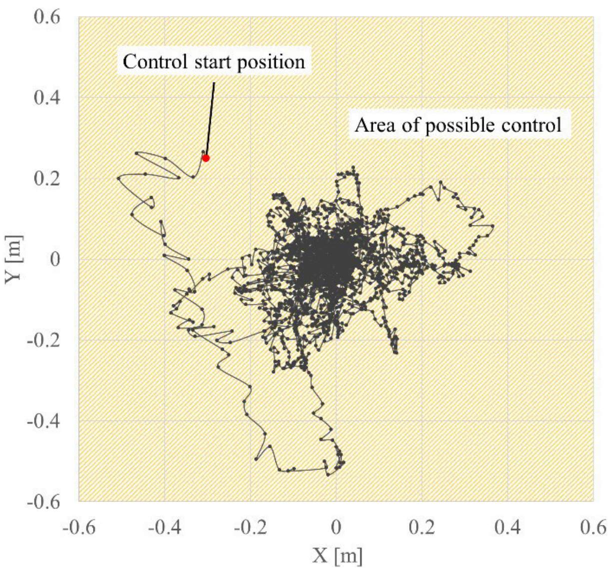

図12　ARマーカー位置推定システム制御によるドローンの軌跡

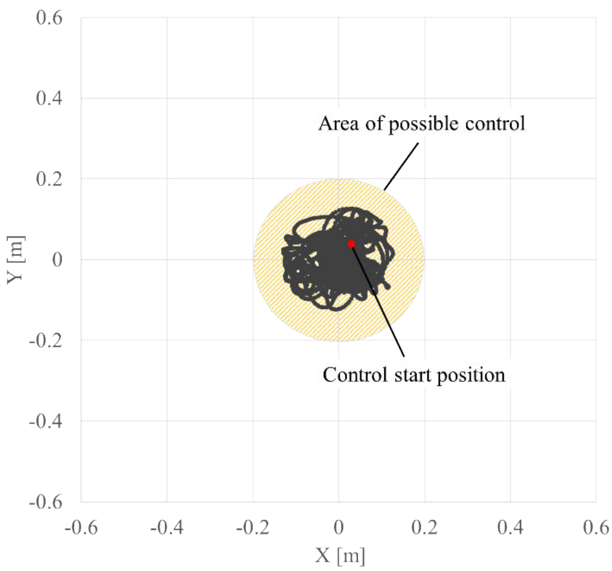

図13　光源位置推定システム制御によるドローンの軌跡

マーカー位置推定システムの軌跡は滑らかではない。これは，カメラの傾き補正に使用したフライトコントローラーのセンサーが実際の傾きとわずかに誤差があるデータを取得した場合に，4 m 先の AR マーカーの位置推定結果には大きな誤差として現れるためである。この誤差は PID 制御の D 成分に大きく現れるため，今回設定した D ゲインより大きくすると，傾き補正による誤差に敏感に反応し，ドローンが急激に傾くため，安定した飛行が困難になることが確認された。

また，AR マーカー位置推定システムはより広い範囲で位置推定および制御が可能であることが確認された。AR マーカー位置推定システムによる制御可能範囲は，カメラの画角に依存し，本実験では短辺が 2.8 m の長方形領域となった。光源位置推定システムによる制御可能範囲は，各受光点で位置推定可能な十分な受光強度の差が得られることによって決定される。本実験では半径 0.2 m の円形領域となった。この結果によって，AR マーカー位置推定システムが広範囲な制御に適している一方で，光源位置推定システムは限定された領域内での高精度制御に適していることが示された。

4. ま　と　め

本研究では，AR マーカー位置推定システムと光源位置推定システムを用いてそれぞれのドローン飛行制御性能を評価した。その結果，AR マーカー位置推定システムは遅延が大きくドローンの傾き補正によって精度が低下するが，カメラの画角に応じて比較的広い範囲で制御可能であるのに対し，光源位置推定システムは高精度かつ低遅延で位置が推定可能であるが，制御可能範囲がビームの照射範囲に限定されることが明らかとなった。この特性から，ワイヤレス電力伝送を行う際には給電スポットからの距離に応じて制御方法を切り替えるアプローチが有効であると考えられる。具体的には，給電スポットから最も遠い領域では RTK-GPS を使用し，給電スポット付近では AR マーカー位置推定システムを使用，給電スポット直上ではマイクロ波ビームを検知し，その位置を推定するシステムを使用することで，ワイヤレス電力伝送における高精度かつ効率的なホバリング制御が実現可能である。本研究の成果は，バッテリー持続時間というドローンの課題を解決するための実用的な基盤技術として貢献が期待される。また，今後は情報遅延および制御周期遅延の改善により，さらに位置制御精度の高いドローンの開発が求められる。

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2025 年は JUIDA 未来創生元年

一般社団法人日本 UAS 産業振興協議会
理事長　鈴木　真二

Technical Journal of Advanced Mobility（次世代移動体技術誌）は 2020 年に創刊され，今年で 6 年目を迎えました。技術だけでなく，制度や，教育活動の分析など次世代移動体に関する論文や報告の発表の場として，国内外から多くの関心を集め，アクセス数も月 1,100 件を超えるまでに成長しました。引き続き，アカデミアのみならず，産業界，研究機関，行政機関など，あらゆる分野からの先進的な取り組みや知見の発表をお待ちしております。

一般社団法人日本 UAS 産業振興協議会（JUIDA）は，2025 年に設立 11 年目を迎えました。この節目にあたり，私たちはこれまでの活動を振り返るとともに，新たなドローンおよび空飛ぶクルマ産業の振興に一層取り組む決意を新たにしています。産業の健全な発展を支えるべく，人材育成，安全運航の推進，関連技術の標準化，そして国際的な連携強化に取り組み，次世代モビリティ社会の構築に寄与してまいります。

小型無人航空機「ドローン」に関しては，2023 年 12 月のレベル 3.5 飛行も新たに制度化され，2024 年度には物流や災害対応での本格運用が全国的に展開されました。特に，能登半島地震災害を契機に，ドローンを活用した被災地支援は社会的認知をさらに高め，物資輸送や捜索活動においてもその充実が官民の目標と掲げられています。JUIDA では引き続き，災害時における迅速な対応体制の強化を進めるべく，自治体，自衛隊との連携を深める取り組みを継続し，また，災害時のドローン活用の知識を体系化した「ドローン防災スペシャリスト教育」プログラムを開始しました。

さらに，2025 年は「空飛ぶクルマ（eVTOL）」の実用化に向けた飛躍の年でもあります。2025 年大阪・関西万博では，eVTOL の試験飛行が会場周辺で実施され，未来技術のショーケースとしての注目を集めることと思います。今後の，日本国内の都市や観光地でも実証実験の加速が期待されます。ドローン技術の発展は，空飛ぶクルマの様々な技術や安全管理にも応用され，両者の技術的融合が進み，次世代エアモビリティーとして体系化されていきます。JUIDA としても，関連産業の発展を後押しすべく，産業界や行政との協力体制を強化し，産業振興支援を積極的に進めてまいります。

2025 年度は，これまでの成果を基盤に，次世代エアモビリティーの社会実装を一層推進すべく，「JUIDA 未来創生元年」と位置づけます。医療，物流，農業，建設など多様な分野での実用化を進め，安全性と利便性の両立を追求し，持続可能な未来社会の実現を目指して取り組んでまいります。Technical Journal of Advanced Mobility も，その一翼を担い，技術と社会をつなぐ架け橋であり続けることをお約束いたします。

2025 年 3 月吉日

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一般社団法人 日本 UAS 産業振興協議会（JUIDA）

JUIDA は、日本の無人航空機システム（UAS）の、民生分野における積極的な利活用を推進し、UAS 関係の新たな産業・市場の創造を行うとともに、UAS の健全な発展に寄与することを目的とした中立、非営利法人として、2014 年 7 月に設立されました。

国内外の研究機関、団体、関係企業と広く連携を図り、UAS に関する最新情報を提供するとともに、さまざまな民生分野に最適な UAS を開発できるような支援を行っています。同時に、UAS が安全で、社会的に許容されうる利用を実現するために、操縦技術、機体技術、管理体制、運用ルール等の研究を行うとともに政策提言を行っています。

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