UMPS: Ultrasound-Microwave-Fused Phase Synchronization for UAV-Based Phased Arrays

Shih-Ming Huang
Graduate Institute of Communication Engineering
National Taiwan University
Taipei, Taiwan
r09942006@ntu.edu.tw

Wei-Cheng Chen
Department of Electrical Engineering
National Taiwan University
Taipei, Taiwan
b07901060@ntu.edu.tw

Yun-Ting Tsai
Graduate Institute of Communication Engineering
National Taiwan University
Taipei, Taiwan
yosikatsai868@gmail.com

Ethan Fang Wu
Department of Electrical Engineering and Computer Science
University of California, Berkeley
California, U.S.A.
Ewu000@berkeley.edu

Shih-Yuan Chen
Department of Electrical Engineering
National Taiwan University
Taipei, Taiwan
shihyuan@ntu.edu.tw

***Abstract*—A wireless ultrasound-microwave-fused phase synchronization (UMPS) method for antenna elements in a UAV-based phased array is presented in this paper. The UMPS includes multiple non-connected modules that follow a leader-follower scheme for positioning and phase synchronization. The only leader is the reference point, to which followers locate their relative position by Time-of-Flight of ultrasound calibrated with microwave signal and synchronize its phase by on-board phase shifters. With a synchronized phase, the UMPS modules can form a phased array with a variable spatial arrangement of antenna elements. In this work, the prototype UMPS exhibits a root-mean-square (RMS) positioning error at 14 mm and a 7.5° RMS phase error for synchronizing a 433 MHz continuous wave RF signal, which is satisfactory for forming a UAV-based phased array.**

***Index Terms*—unmanned aerial vehicles (UAV), phased arrays, phased shifters**

I. Introduction

An unmanned-aerial-vehicles-based (UAV-based) phased array is formed by antenna elements separately carried by multiple UAVs. By relaxing the limit on its spatial arrangement of antenna elements, the UAV-based phased array has potentially better deployment flexibility and performance than conventional phased arrays.

The concept of the UAV-based phased array was proposed by Breheny *et al.* [1] and validated by simulations. Their results show that position sensing is the core requirement to synchronize the radio frequency (RF) signal for beamforming (RF_{BF}) for a practical UAV-based phased array. With a root-mean-square (RMS) positioning error at 0.03 wavelength (λ), the phased array synthesized by UAVs has a 3-dB loss in directivity compared to that of an ideally positioned phased array, which is satisfactory for practical applications [1]. In this work, we will propose a position-sensing and phase-synchronization system for a practical UAV-based phased array and verify it through a prototype system.

The requirements of position sensing for a UAV-based phased array include: high accuracy, high update rate, and distributed computation scheme. The accuracy should be within 0.03λ to synthesize a satisfactory radiation pattern. With a sufficiently high update rate, the phase shifters on UAVs can compensate for the effect of sudden displacement. Under a distributed computation scheme, every UAV can share the computation workload of positioning, ensuring the scalability of the UAV-based phased array.

To realize a positioning module that satisfies the above-mentioned requirements, we referred to existing indoor positioning methods [2][3]. Vision-based positioning has the highest accuracy (several mm), but its high computation cost of image processing limits the update rate at $1-20$ Hz [4]. RF-based positioning systems, including Wi-Fi, Bluetooth, ultra-wideband, and RFID, can only reach an accuracy at tens of cm, insufficient for a UAV-based phased array. Finally, ultrasound (US)-based positioning has an accuracy at several cm and a high update rate. Although the multipath effect of US may disrupt the accuracy of indoor positioning, the effect is not significant for UAVs flying outdoors. Therefore, we adopt US, fuse it with the microwave signal in our positioning method, and propose an ultrasound-microwave-fused phase synchronization (UMPS) system.

The scenario of applying UMPS to a UAV-based phased array is shown in Fig. 1. The leader first broadcasts the desired modulated RF_{BF} signal (with a carrier frequency of 433 MHz in our prototype) and UMPS signals, including two pulse trains of 40 kHz ultrasonic signal (f_{40K}) and 915 MHz microwave signal (f_{915M}), simultaneously. Followers, acting as relays for RF_{BF} signal, locate themselves by retrieving the arrival time difference of f_{40K} and f_{915M} signals, and synchronize the phase of its RF_{BF} signal with that of the leader. By relaying and adding proper phase shift to the received RF_{BF} signal, the followers can synthesize a desired beam pattern with the

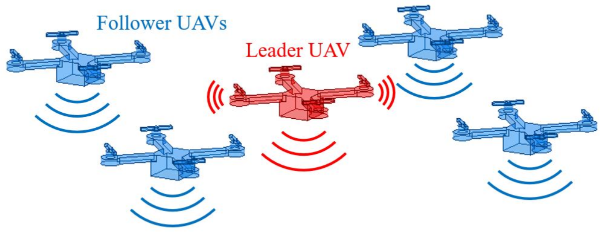

Fig. 1. Scenario of a UMPS-incorporated UAV-based phased array.

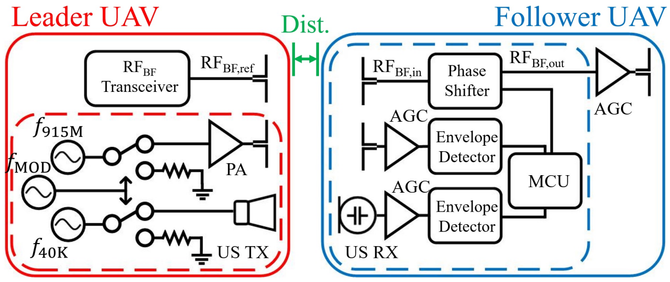

Fig. 2. Block diagram of UMPS on a UAV-based phased array. The red/blue solid lines mark the blocks on the leader/follower UAV, and the dashed lines mark the UMPS modules on the leader/follower.

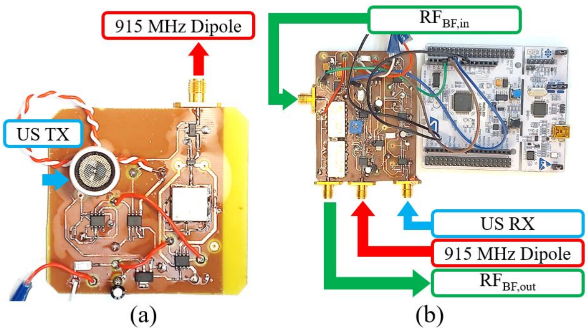

Fig. 3. Photographs of UMPS prototype modules for (a) leader and (b) follower. The arrows indicate the directions of signals.

leader, forming a UAV-based phased array.

As a proof of concept, we tested the 1D-positioning and phase synchronization capabilities of the proposed UMPS. The experimental results show that the RMS positioning error of the proposed UMPS is 14 mm, and the update rate is up to 59 Hz. The phase synchronization of $\mathrm{RF_{BF}}$ signal at 433 MHz is achieved with 7.5° RMS phase error. Because the computation of positioning and phase compensation is done at the followers, the workload remains the same no matter how many followers are added to the array. The proposed UMPS is promising to realize a practical UAV-based phased array. Applicable domains include radar, wireless power transfer, B5G/6G base stations, and ground terminals for LEO satellite communications.

II. UMPS Design

A. Microwave-Augmented Ultrasound Positioning

In a UMPS system, the followers locate themselves by measuring the time difference (t_d) between the arrival time of $f_{40\mathrm{K}}$ ultrasonic and $f_{915\mathrm{M}}$ microwave signals, which are simultaneously broadcasted by the leader. Because the speed of microwave signal is much faster than the US, t_d between them is used as the approximate Time-of-Flight (ToF) of the US signal. Therefore, the distance can be written as:

$$Distance = V_{\mathrm{US}} \times \mathrm{ToF} \approx V_{\mathrm{US}} \times t_\mathrm{d}, \tag{1}$$

where V_{US} is the velocity of US (346.15 m/s at $25°C$). In other words, the microwave signal is used as the timestamp in UMPS instead of complex synchronization techniques.

According to (1), the accuracy of distance measurement (Δd) can be determined by the resolution of t_d, which is determined by the sampling frequency (f_s) of the analog-to-digital converter (ADC) used in the UMPS module. Thus, Δd can be written as:

$$\Delta d = V_{\mathrm{US}} \times \Delta t_\mathrm{d} = \frac{V_{\mathrm{US}}}{f_s}. \tag{2}$$

With an ADC having 133 kHz sampling rate, the expected Δd of the proposed UMPS is 2.6 mm at $25°C$.

B. Schematics of UMPS modules

Fig. 2 shows the block diagram of the UMPS modules on a UAV-based phased array. The UMPS on the leader has two signal sources, a $f_{40\mathrm{K}}$ source feeding to a US transmitter and a $f_{915\mathrm{M}}$ source feeding to a 915-MHz dipole antenna. Modulated by the same Amplitude-Shift-Keying (ASK) modulator, the two signals are simultaneously broadcasted at a rate f_{MOD}, which is 100 Hz in our prototype module. Then, the UMPS on the follower receives the modulated $f_{40\mathrm{K}}$ and $f_{915\mathrm{M}}$ signals. Amplified by automatic gain control amplifiers (AGC) and converted to envelope, the two signals are post-processed by a microcontroller unit (MCU). Retrieving t_d, the arrival time difference, by an efficient edge detection algorithm [5], the distance to the leader UAV and the corresponding propagation phase delay of the $\mathrm{RF_{BF,in}}$ signal can thus be calculated by the MCU. With the phase delay compensated by the phase shifter, the phase of $\mathrm{RF_{BF,out}}$ can be synchronized with the reference signal ($\mathrm{RF_{BF,ref}}$) on the leader, or added with additional phase shift for beam steering. Finally, an AGC amplifies the $\mathrm{RF_{BF,out}}$ signal to compensate the path loss from the leader to the follower and the insertion loss of the phase shifter to maintain the desired level of radiating power among the group of UAVs. The model name of the off-the-shelf components used in the prototype UMPS modules are listed in Table I and the photos are shown in Fig. 3.

III. Measurement Setup

To test our prototype UMPS modules, we vary the distance between a pair of prototype leader and follower UMPS modules, and see if the follower UMPS module can synchronize the phase of $\mathrm{RF_{BF,out}}$ with $\mathrm{RF_{BF,ref}}$, which is a 433 MHz continuous wave in this preliminary experiment. We use a vector network analyzer (VNA) (RS ZVL) to inspect

TABLE I
OFF-THE-SHELF COMPONENTS

Functions	Manufacturer	Model Name
f_{40K} & f_{MOD} Source	Texas Instrument	LM555
f_{915M} Source	Crystek	CVCO55CL-0800-0980
AGC	Analog Devices	AD8367
Schottky diode	Infineon	BAS52-02V
Schottky diode	Skyworks	SMS7630-079LF
Phase Shifter	Mini Circuits	JSPHS-661+
Op. Amp.	Texas Instrument	LM358
SPDT Switch	Skyworks	AS169-73LF
PA	Mini Circuits	GALI-59+
US TX/RX	N/A	TCT40-16T/R
MCU	STMicroelectronics	NUCLEO-L476RG

the phase difference between $RF_{BF,ref}$ and $RF_{BF,out}$, with the RF_{BF} transceiver in Fig. 2 replaced by the port 1 of VNA, and the $RF_{BF,out}$ directly connected to port 2, by measuring the phase of S_{21}. The distance between the two UMPS modules is controlled by an electronic slider (OrientalMotor ELSEZSHM6H130AZAC), which has an accuracy of 50 μm. The experimental setup is shown in Fig 4.

IV. RESULTS

The 1-D positioning test is performed by linearly varying the distance between the two UMPS modules in a range of $30 - 1330$ mm. The distance reading of the UMPS module versus time is plotted in Fig. 5, denoted as "Measured", along with the reading from the slider itself, which is denoted as "Ideal". One can see that they agree very well verifying the positioning capability of the proposed UMPS module. The results show that UMPS has an RMS positioning error within 14 mm. Estimated by the 0.03λ criterion [1], the theoretical maximum frequency of applicable RF_{BF} is 642 MHz. The calculation time for single positioning is 17 ms, including 10 ms for measuring the envelope of f_{40K} and f_{915M} signals and 7 ms for processing, equivalent to 59 Hz update rate.

The phase synchronization capability is tested by linearly varying the distance between 350 and 700 mm, which is equivalent to 0.5 and 1λ of 433 MHz RF_{BF} signal. The reading of phase error between $RF_{BF,ref}$ and $RF_{BF,out}$ signals and the trace of distance variation versus time is shown in Fig. 6. To demonstrate the effect of phase synchronization, we disable/enable the phase shifter in the proposed UMPS module to show the results with/without phase synchronization in Fig. 6(a) and 6(b), respectively. Without phase synchronization, the phase error is linearly dependant on the distance variations, with an RMS phase error at 122.7°. With phase synchronization, the phase error is kept within the range from $-11°$ to $13°$, with an RMS phase error at 7.5°.

We can observe a high consistency between the RMS positioning and phase error. By dividing the measured RMS positioning error (14 mm) with the wavelength of 433 MHz RF_{BF} signal, we can obtain the estimated RMS phase error to be 7.3°, which agrees with the measured RMS phase error (7.5°). The consistency shows that the phase error of UMPS is dominated by the positioning error.

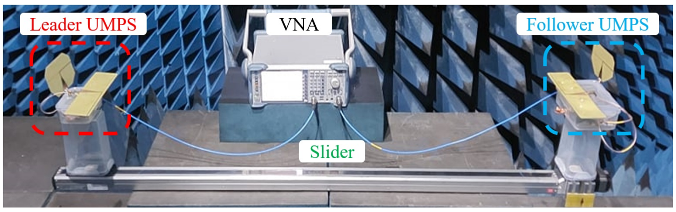

Fig. 4. Experimental setup for phase synchronization with dynamic distance variation. The leader is moved by the slider and the follower is fixed. Both the leader and follower modules are placed in plastic boxes and mounted onto the slider.

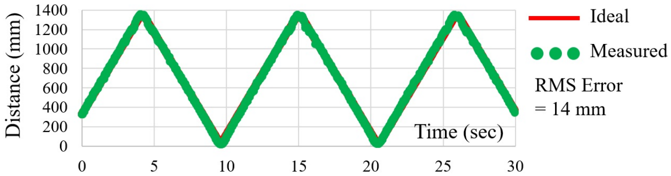

Fig. 5. Distance estimation based on the measured signals by UMPS plotted with ground truth (Ideal).

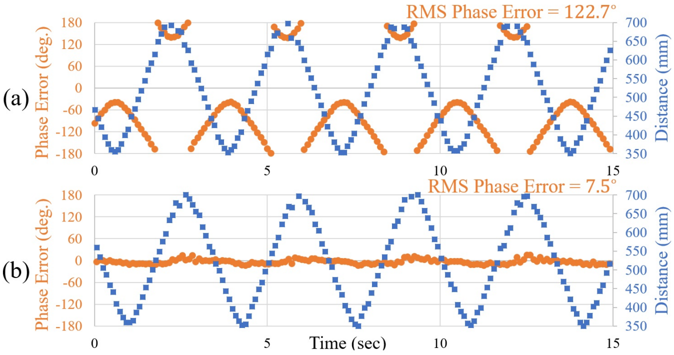

Fig. 6. Positioning results (blue squares) and phase error of $RF_{BF,out}$ (orange dots) (a) w/o and (b) with phase synchronization by UMPS.

V. CONCLUSIONS

Through the preliminary experiments, we validated the positioning and phase synchronization capabilities of the prototype UMPS modules. An RMS phase error of 7.5° in the desired RF signal are achieved along with 14-mm RMS positioning error and 59-Hz update rate. Incorporated with a 2D-positioning algorithm, RF transceivers, and AGCs, UMPS can be exploited to realize a practical UAV-based phased array.

VI. ACKNOWLEDGMENT

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