

A Passive Spread Spectrum Sound-Based Local Positioning System for Robots in a Greenhouse

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Graduate School of Agriculture
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Thesis

Submitted in partial fulfillment of the requirements for the degree of doctor in
agricultural science

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Chapter 1 *Introduction*

1.1 Background

Agricultural robot has been researched in the past few decades to solve shortage of labor and handle the tedious work (Kondo et al., 2004). Many robots have been researched and commercialized in the open field, such as rice transplanter (Nagasaka et al., 2009), combine harvester (Iida et al., 2013), and so on. The greenhouse has controlled environments and provides regulated climatic conditions for plants (“Greenhouse,” 2020). There seldom has the report on the commercialized fully automatic robots in a greenhouse, even though to date a number of robots have been developed for vegetable and fruit production in a greenhouse, such as tomato harvesting robot (Kawamura et al., 1984), strawberry harvesting robot (Arima et al., 2004; Kondo et al., 1998; Zhang et al., 2016), pesticide spraying robot (Liu et al., 2011; Nakao et al., 2017), crop monitoring robot (Aravind and Raja, 2016) and so on. These robots are working on ground with low speed, so they need to carry more loads, and they are designed as large and heavy robots. The most greenhouse robotic systems are slow, heavy and expensive and hard to commercialize in horticultural practice. For example, Shibuya company (Shibuya Seiki Co., LTD) produced a strawberry harvesting robot that comes with a \$50,000 price tag and more than 300 kg weight. To commercialize robots in greenhouse, low cost and autonomous platform is needed.

We proposed a new robotic scheme (Fig.1.1) in the greenhouse with small distributed crawler robots and the quadcopter. Here the ridge cultivated strawberry is taken as an example to illustrate the new robotic scheme. The moving speed of the crawler robot and quadcopter can be set as 0.3 m/s with less than 10 kg weight. Comparing with the conventional robotic system, the proposed new scheme has less weight, lower price, higher working efficient due to easiness to add the number of

robots. The crawler robots can finish certain works such as irrigation, fertilization, harvesting. Such function can be set into a modular unit.

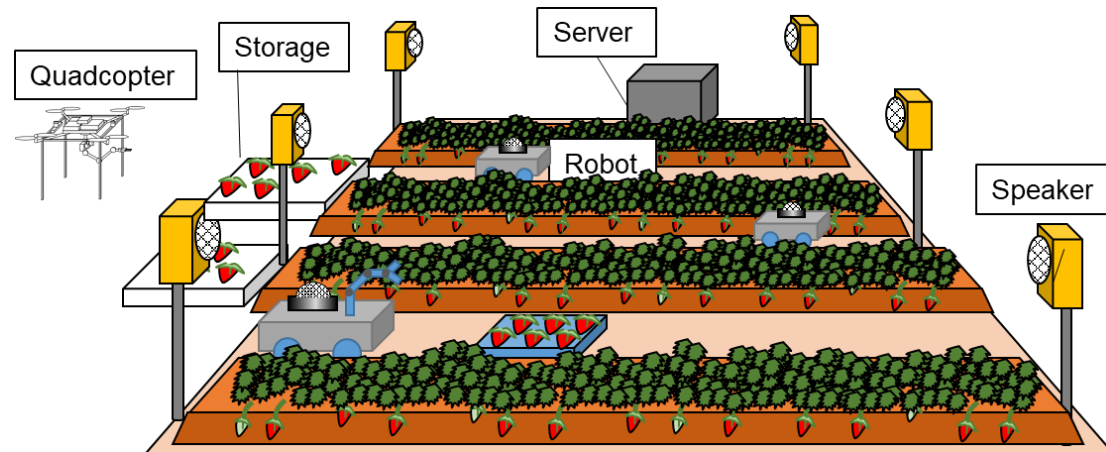


Fig.1.1 New robotic scheme in a greenhouse

These years the multicopter draw people's attention since it is a cheap, light and convenient platform. A multicopter, also called a multirotor helicopter or multirotor, is a kind of micro Unmanned Aerial Vehicle (UAV) propelled by multiple rotors. The commercialized quadcopters, including Parrot, Syma X and Phantom, normally have similar size and structure in order to make them easier to carry. Since it has faster speed and easier to move over the obstacles, it has been applied for applications such as measuring environmental variables in greenhouses (Roldan et al., 2015), monitoring health of crops by Normalized Difference Vegetation Index (NDVI) (Bhandari et al., 2012; Calero et al., 2018), harvesting (Fig.1.2) and so on. In the proposed scheme, the quadcopter can monitor the health of plants by a top view, generate the map of mature strawberries to guide the harvesting robots.



Fig 1.2 A multicopter work in the greenhouse

A positioning accuracy within 30 mm is needed to locate robots and guide them in the operating routine in greenhouse since the distance between ridges in a greenhouse is around 300 mm and the possible width of the robot is around 240 mm. Normally, a Global Navigation Satellite System (GNSS) guides the multicopter in the field, as well as guiding combine robots in the field (Iida et al., 2013). But the GPS has weak signal and low accuracy in indoor environments because no line-of-sight transmission between the receiver and satellites (Gu et al., 2009). High accuracy positioning can help the multicopter to handle ridges and fixed obstacles in greenhouse. A number of other methods have been researched for localization in GPS denied environment. The rails (Hayashi et al., 2014) fixed on the ground can be positioning system for the heavy robot within 10 mm accuracy, while it's expensive and difficult to set new rails. The electromagnetic navigation system (Liu et al., 2011) buried sensors in the soil to estimate the position of the robot. Radio Frequency Identification (RFID) (Choi et al., 2011; Huang et al., 2008; Ruiz-Garcia and Lunadei, 2011; Shirehjini et al., 2012) also

can be used for estimating the position of a robot by setting multiple sensors on the ground, while these researches only have experiment in indoor environment and the coverage is less than 10 m² with around 63.6 mm accuracy. The most famous commercialized indoor positioning system is Ultra Wide Band (UWB) (Delamare et al., 2019; Mazhar et al., 2017), which normally is an active structure with around 100 mm accuracy. The limitation of UWB is not enough accuracy and possible signal interference (Nikookar and Prasad, 2009). The Sound-based Positioning System (Atri Mandal, 2005; Medina et al., 2013; Rishabh et al., 2012) can reach 100 m² coverage and centimeter accuracy. Therefore, these Sound based positioning system is an attractive positioning system for use in the greenhouse, given its high measurement accuracy with centimeter accuracy and low cost within thousand dollars (Randell and Muller, 2001) because the distance is measured by sound wave, which has many commercialized hardware.

To date, there are two major sound-base positioning system: ultrasound-based positioning system (UltraPS) (Ghidary et al., 1999) and spread spectrum sound-based local positioning system (SSSLPS) (Widodo et al., 2014). The UltraPS has many commercialized products since its positioning accuracy can reach Root Mean Square Error (RMSE) of 20 mm with cheap price, but with low noise tolerance. To increase the noise tolerance of SPS, the SSSPS was developed and used for estimation of distance measurement in a 30 m × 30 m area, and the Root Mean Squared Error (RMSE) of average two-dimensional (2D) positioning accuracy of this system was 20 mm (Widodo et al., 2014).

1.2 Problem statement

Our previous system was an active structure that set speaker on the robot, which was heavy and difficult for tracking multiple robots due the noise interference. For

positioning multiple robots in the greenhouse, the passive positioning system that set microphone on the robot and speakers fixed at corners should be developed to reduce the interference between each channel.

It is necessary to know the orientation of the robots for controlling the direction of movement. Usually, the geomagnetic sensor is used for measuring orientation, while its accuracy may be interfered with iron ore (underground), iron materials, electrical machines and electromagnetic waves (Tu et al., 1997). An alternative method uses two positions on the robot to measure the orientation (Koura et al., 2001). The previous research reached around 2° accuracy of orientation estimation (Dong et al., 2013) to control the ground robot, and 2° orientation (yaw) accuracy (Tomáš, 2011) of controlling the orientation of a multicopter. For the orientation estimation, the 2° accuracy is necessary. The two known positions on the robot can provide a vector of the robot (Shirehjini et al., 2012), so the orientation of a robot can be estimated by the spread spectrum sound-based local positioning system (SSSLPS).

There are two factors that decide the SSSound to be successfully detected: acoustic interference by quadcopter noise and doppler shift in received signal. Acoustic noise spectrum of a quadcopter was measured by previous research using DJI Phantom 2 with four sets of propellers at different thrust (Intaratep et al., 2016). They found the motor noise mainly exists at 6 kHz. The noise of quadcopter in SSSound range (over 10 kHz) was aerodynamical noise caused by propellers hitting the air. So, the noise tolerance of SSSLPS against the quadcopter noise will be evaluated in this research to judge the possibility of using SSSLPS for positioning a quadcopter.

Our team developed Doppler shift compensation algorithm to solve the doppler shift effect on sound wave (Widodo et al., 2013) for a ground robot. While this method used an extra ultrasound for detecting the frequency shift, this ultrasound may interfere

with the SSSound. A new compensation algorithm should be developed by only use of SSSound signal and can compensate the frequency shift on the SSSound.

1.3 Research objectives

The overall objective in this study is to develop the passive SSSLPS for a robot in a greenhouse.

It includes three sub-objectives:

1. Orientation estimation by SSSLPS using two microphones on a robot.
2. Evaluate the noise tolerance of SSSLPS against the quadcopter noise.
3. Develop and evaluate doppler shift compensation algorithm for a moving robot.

1.4 Thesis outline

This thesis includes three parts: (1) the basic of passive SSSLPS; (2) orientation estimation by SSSLPS using two microphones on the robot; (3) evaluating noise tolerance and compensating doppler shift that decide the SSSLPS can work for the robotic scheme or not.

Chapter 2 gives general introduction about the passive SSSLPS. It introduces the distance measurement and position estimation by SSSLPS. The general hardware is listed in this chapter.

Chapter 3 describes the orientation estimation by SSSLPS using two microphones. Two methods are compared in an experiment conducted in a greenhouse. The factors

that affect the accuracy of orientation estimation by the two methods are evaluated.

Chapter 4 evaluates the noise tolerance of the SSSLPS against the multicopter noise. The acoustic noise spectrum of the multicopter is evaluated using several propellers. Then the properties of SSSound are compared to evaluate the noise tolerance. Finally, an experiment in the greenhouse is used to evaluate the positioning accuracy using SSSLPS on a quadcopter.

Chapter 5 describes the proposed doppler shift compensation algorithm for the SSSLPS. The experiment compares the performance of doppler shift compensation with constant velocity and accelerated velocity. The positioning accuracy is conducted with the Vicon system, which is a machine vision-based positioning system with 0.1 mm accuracy.

Chapter 6 summarizes the dissertation and some possible future research topics for commercializing the SSSLPS.

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Chapter 2 *Spread spectrum sound-based local positioning system*

2.1 Distance measurement by SSSound

The basic principle for distance measurement is Time of Flight (TOF) based on the flight time of SSSound signal from speaker to microphone. First the speaker emits trigger signal (radio wave) and SSSound signal to microphone. When the system detects trigger signal, which is using radio frequency wave and has high speed than sound wave, the microphone begins to record sound signal. Then the cross-correlation calculation can help to get the arrival time of SSSound signal. TOF is estimated by the difference of arrival time and trigger signal. The sound velocity can be calculated from environmental temperature. So, the distance from speaker to microphone can be estimated by multiplying sound velocity and TOF. Here taking the typical SSSound for an example to illustrate the distance measurement.

The SSSound is generated by M-sequence, which is a kind of pseudo-noise sequence and has a good performance at cross-correlation. A previous research (Sawlikar and Sharma, 2011) compared the general pseudo noise including M-sequence, Kasami sequence, gold sequence, and concluded the correlation of M-sequence only has a signal peak, which the arrival time is easier to be detected. Then it was multiplied by carrier waves. Here, Binary Phase Shift Keying (BPSK) modulation was used.

Fig.2.1 illustrates the generation of SSSound. SSSound signal was generated by the following equation:

$$s(n) = \text{round} \left\{ \sin \left[\frac{2\pi f_c (n-1)}{f_s} \right] \times M(ms) \right\} \quad (2.1)$$

with

$$ms = \text{floor} \left[\frac{f_{chip}(n-1)}{f_s} \right] \quad (2.2)$$

where $n=1,2,3 \dots SSS_n$, SSS_n is the length of SSSound (1/96 ms), M is matrix of M-sequence, f_c is carrier waves, f_s is sampling frequency (96 kHz) and f_{chip} is chip rate. The properties of a typical SSSound were summarized in Table 2.1.

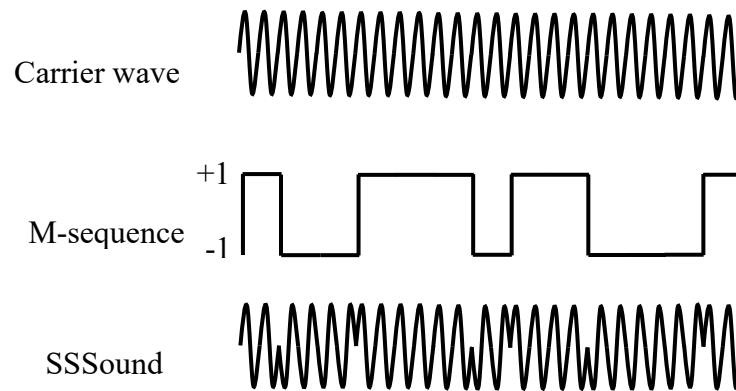


Fig.2.1 Generation of SSSound

Table 2.1 Typical property of spread spectrum sound

Property	Value/Remark
Sampling frequency (f_s)	96 kHz
Sampling bit	16
M-sequence length	1024
Modulation	BPSK
Carrier wave frequency (f_c)	24 kHz
Chip rate (f_{chip})	12 kcps

The frequency property of the SSSound is shown in Fig.2.2. Since the environmental sound noise was mainly in hearing range, the side lobe from 0 to 12 kHz was cut during calculating the cross-correlation to decrease noise interference. Meanwhile to keep good cross-correlation performance, the side lobe from 36 kHz to 48 kHz was also cut. The SSSound without side lobes still has good performance at cross-correlation.

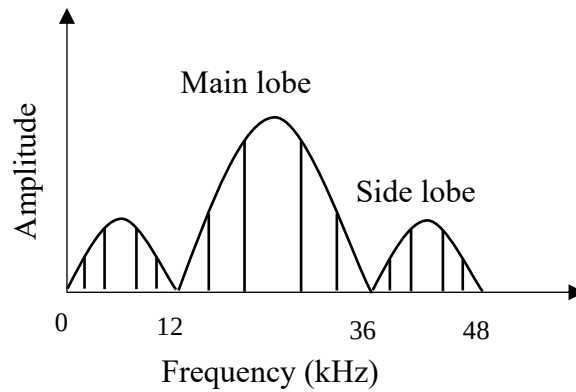


Fig.2.2 Frequency property of SSSound

We assume the maximum measurement distance is 50 m. If the sound velocity is 340 m/s, the necessary length for calculation cross-correlation is 14118 ($= 96000 \times 50 / 340$). So the maximum length of received signal should be 22302 ($= 14118 + 8184(\text{length of replica signal})$). After emitting trigger signal, received signal with SSSound signal was captured by microphones. Then correlation value was calculated to find the TOF by estimating the peak of cross-correlation by Eq.2.3. Then a calculation of Eq.2.4 is conducted to find the threshold that can get the peak of cross-correlation.

$$c(t) = \sum_{n=0}^{N-1} s(n)r(n+t) \quad (2.3)$$

$$c_{th} = C_{ave} + 4\sigma_{corr} \quad (2.4)$$

where t is the time of received data, s is transmitted signal, r is received signal, N is length of received signal (1/96 ms), C_{ave} and σ_{corr} is average absolute and standard deviation of cross-correlation, respectively.

To decrease the processing time, Fast Fourier Transform (FFT) was used. The cross-correlation of SSSound signal and received signal can be calculated by the Inverse Fast Fourier Transform (IFFT) of their cross-spectrum as following steps,

- a) Calculate FFT of the received signal $R(b)$
- b) Calculate FFT of the replica signal $S(b)$
- c) Calculate cross-spectrum of this signal pair as

$$\phi_{sr}(b) = S^*(b)R(b) \quad (2.5)$$

where $S^*(b)$ is complex conjugate of signal $S(b)$, $R(b)$ is complex spectrum of signal $R(b)$.

- d) Take IFFT of the calculated cross-spectrum $\phi_{sr}(b)$.

Fig.2.3 shows an obvious correlation value with a high peak. The time of this peak is c_{max} , so the flight time from speaker to microphone is c_{max} (1/96 ms).

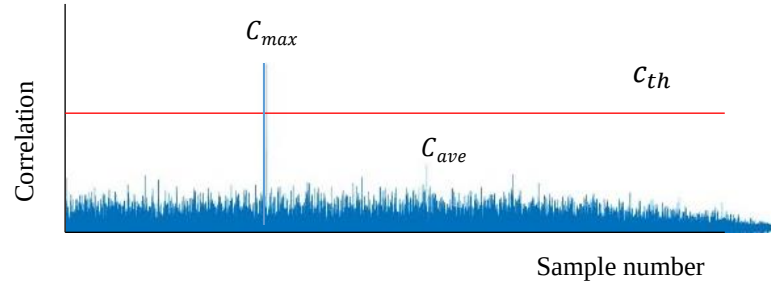


Fig.2.3 Correlation value from received signal

The sound velocity is used to calculate the distance (d_j) from speaker to microphone i by the following equation,

$$v_s = 331.5 + 0.61\left(\frac{T_i + T_s}{2}\right) \quad (2.6)$$

$$d_i = v_s \Delta t \quad (2.7)$$

where T_i is the temperature at microphone i (M_i), T_s is the temperature at speaker, v_s is the speed of sound wave (m/s).

2.2 Position estimation

At last three known distances and known speakers' position can get 3D position using trilateration method (Fig 2.4). The blue circles in Fig.2.4 means the four measured distance by SSSLPS. The overlap area (black point) is the estimated position. After getting the distance from a microphone to speakers, an iterative least squares method (Abdullahi et al., 2015; Shiigi et al., 2017) was used to estimate position.

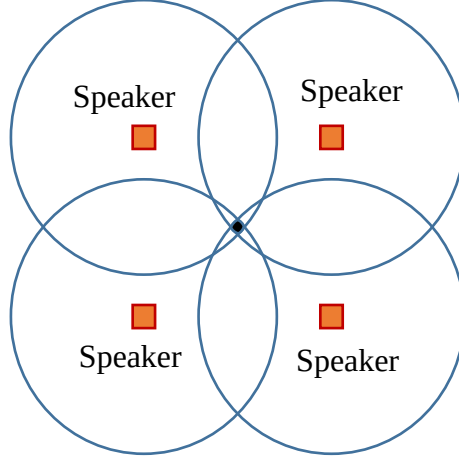


Fig.2.4 Position estimation by trilateration

Here GPS-like system was used to illustrate the position calculation from four distances. First, let the microphone be located at an unknown position $S = (x_m, y_m, z_m)$ and the four speakers be located at known position $M = (x_i, y_i, z_i)$. So the distance d_{si} from speaker to microphone can be expressed as,

$$d_{si} = \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2 + (z_m - z_i)^2} \quad (2.8)$$

which is a measured distance by SSSound based distance calculation method. In order to estimate the microphone position, an initialized $m^0 = (x_m^0, y_m^0, z_m^0)$ was given to microphone and is used to calculate the distance from speaker to microphones (d_{si}^0),

$$d_{si}^0 = \sqrt{(x_m^0 - x_i)^2 + (y_m^0 - y_i)^2 + (z_m^0 - z_i)^2} \quad (2.9)$$

The difference of these distance (i.e. d_{si} and d_{si}^0) which is

$$\Delta d_{si} = d_{si} - d_{si}^0 \quad (2.10)$$

These differences ($\Delta d_{si} = \nabla d_{si}$) are used to determine partial difference ($\Delta x_m, \Delta y_m, \Delta z_m$) for correcting the value of x_m^0, y_m^0 and z_m^0 . The following equation is for

calculating the partial difference,

$$\nabla d_{si} = \frac{\partial d_{si}^0}{\partial x_m} \Delta x_m + \frac{\partial d_{si}^0}{\partial y_m} \Delta y_m + \frac{\partial d_{si}^0}{\partial z_m} \Delta z_m \quad (2.11)$$

where

$$\frac{\partial d_{si}^0}{\partial x_m} = \frac{x_m^0 - x_i}{d_{si}^0}$$

$$\frac{\partial d_{si}^0}{\partial y_m} = \frac{y_m^0 - y_i}{d_{si}^0}$$

$$\frac{\partial d_{si}^0}{\partial z_m} = \frac{z_m^0 - z_i}{d_{si}^0}$$

Here three distances can get the partial difference, while four distances can improve the accuracy. For getting partial difference by four distances, equation 2.11 was changed into the following matrix,

$$\Delta d_{si} = A \begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix} \quad (2.12)$$

$$\text{where, } A = \begin{bmatrix} \frac{x_m^0 - x_1}{d_{s1}^0} & \frac{y_m^0 - y_1}{d_{s1}^0} & \frac{z_m^0 - z_1}{d_{s1}^0} \\ \frac{x_m^0 - x_2}{d_{s2}^0} & \frac{y_m^0 - y_2}{d_{s2}^0} & \frac{z_m^0 - z_2}{d_{s2}^0} \\ \frac{x_m^0 - x_3}{d_{s3}^0} & \frac{y_m^0 - y_3}{d_{s3}^0} & \frac{z_m^0 - z_3}{d_{s3}^0} \\ \frac{x_m^0 - x_4}{d_{s4}^0} & \frac{y_m^0 - y_4}{d_{s4}^0} & \frac{z_m^0 - z_4}{d_{s4}^0} \end{bmatrix}.$$

For partial difference, equation 2.12 was changed into the following matrix with pseudo inverse matrix,

$$\begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix} = (A^T A)^{-1} A^T \begin{bmatrix} d_{s1} \\ d_{s2} \\ d_{s3} \\ d_{s4} \end{bmatrix} \quad (2.13)$$

After obtaining the partial difference, these values are then used to update the estimated position,

$$\begin{bmatrix} x_m^1 \\ y_m^1 \\ z_m^1 \end{bmatrix} = \begin{bmatrix} x_m^0 \\ y_m^0 \\ z_m^0 \end{bmatrix} + \begin{bmatrix} \Delta x_m \\ \Delta y_m \\ \Delta z_m \end{bmatrix} \quad (2.14)$$

This iteration will run 50 times to get the final estimated position.

2.3 Architecture of the proposed positioning system

There are two main location architectures: with either a speaker or a microphone (Mic) set on the quadcopter. The inverse GPS-like system (active mobile architecture) uses a speaker on the robot to transmit signals to each of the microphones set around the boundary (Fig.2.5 (a)). For GPS-like system (passive mobile architecture), several transmitters are placed at known positions and are used to transmit their location on a wireless channel (Fig.2.5 (b)) (Smith et al., 2004). The GPS-like system can easily track multiple objects, while the inverse GPS-like system doesn't suffer near-far problems (Widodo et al., 2013). In our research, we assume the maximum measured distance is 50m since 40×40 m is the typical greenhouse size in Ehime Prefecture.

In our experiment, the wire linked system and wireless system are used. Normally the wire linked system (Fig.2.6) is used for static measurement because of the only delay is caused by the filters of the speaker.

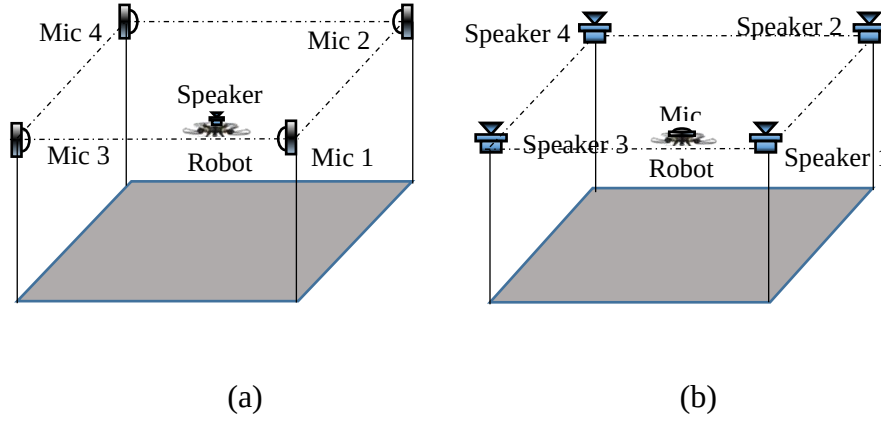


Fig.2.5 Configuration of inverse GPS-like (a) and GPS-like (b) system

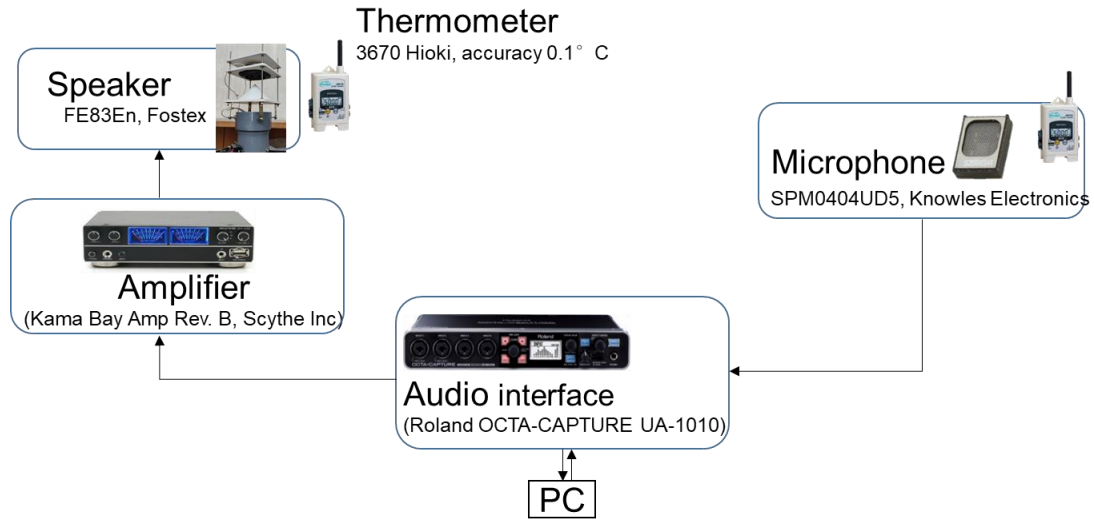


Fig.2.6 SSSLPS with wire linked system

The frequency response curve of the speaker (FT28D, Fostex) is shown in Fig.2.7. A 3D printed cone (Fig.2.8) is fixed on the speaker to emit the omnidirectional acoustic signal. The microphone (SPM0404UD5, Knowles Electronics) size is 4.7×3.8 mm within 1 dollar. Its frequency response curve is shown in Fig.2.9. The microphone was connected with an audio interface (Roland OCTA-CAPTURE UA-1010, Fig.2.10) with 96 kHz sampling frequency, which can record sound signal from 0 to 48 kHz (specifications in Table 2.2). The speaker was fixed on the stand at the corner, and

connected with amplifier (Scythe SDA-2100, Fig.2.11) and audio interface. The sound pressure level of the speaker is adjusted around 85 dB by emitting white noise using the noise meter (LA-4440, Ono Sokki, Fig.2.12). The properties of noise meter are shown in Table 2.3.

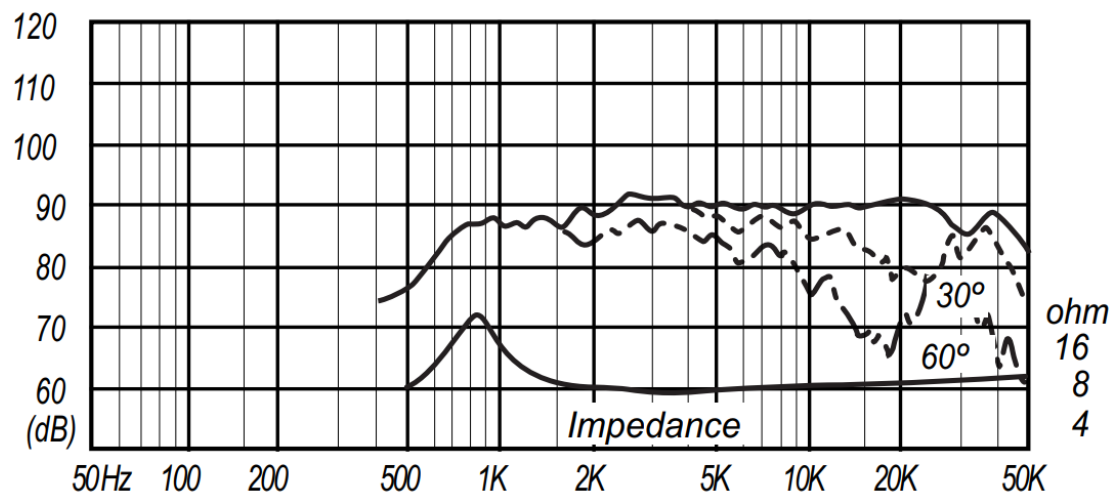


Fig.2.7 Frequency response curve of speaker



Fig.2.8 Speaker with cone

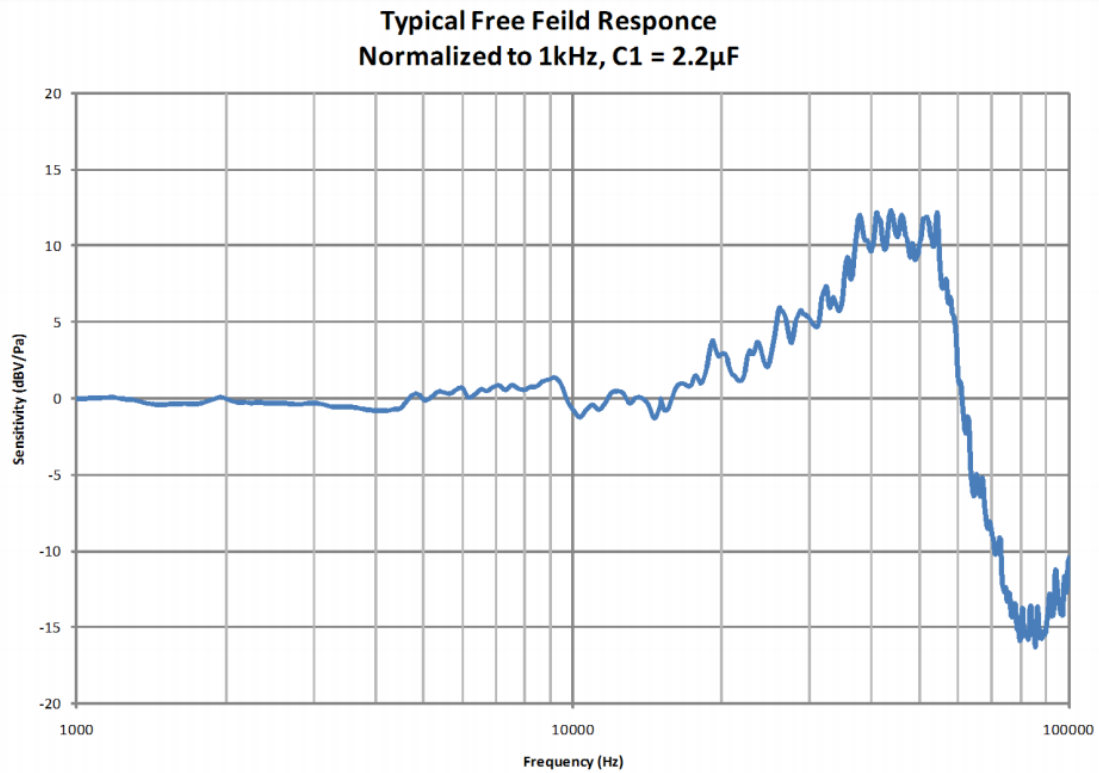


Fig.2.9 Frequency response curve of microphone



Fig.2.10 Audio interface (www.roland.com/global/products/octa-capture/)

Table 2.2 Specifications of audio interface

Amount of channels	Sampling frequency=44.1kHz、48kHz、96kHz Recording = 12 channel Playback = 10 channel Sampling frequency=192kHz Recording = 4 channel Playback = 4 channel
Signal processing	PC interface=24bit AD/DA converter= 24 bit Internal processing= 40 bit
Sampling frequency	AD/DA converter = 44.1kHz, 48kHz, 96kHz, 192kHz DIGITAL (IN/OUT) =44.1kHz, 48kHz,96kHz
Specified input level (variable)	INPUT 1~6 (XLR type) =-56~-6dBu INPUT 7~8 (XLR type) =-50~+0dBu INPUT 1~8 (TRS standard type) =-46~+4dBu
Specified output level	OUTPUT 1~8=+0dBu (バランス)
Frequency characteristic	192.0kHz = 60kHz~90kHz (+0/-8dB) 192.0kHz = 20Hz~60kHz (+0/-2dB) 96.0kHz = 20Hz~40kHz (+0/-2dB) 48.0kHz = 20Hz~22kHz (+0/-2dB)
Noise level	INPUT 1~2→OUTPUT 1~2 = -87dBu typ. (GAIN: min.、Input 600 Ω termination、IHF-A) ※ InternalDirect Monitor Mixer Configuration: Stereo Link=on Input channel・Fader = Unity
Dynamic range	AD INPUT 1~8=104dB typ. (GAIN: min.) DA (OUTPUT 1~8=113dB typ.)
Interface	USB2.0 (Hi-Speed) Digital input / output (Coaxial・type) MIDI Input / output
Power	DC9V (AC adapter)
Current	1.45A



Fig.2.11 Amplifier (www.head-fi.org)

Table 2.3 Specifications of noise meter

Applicable standard	IEC 61672-1 : 2002 Class 1
Microphone	1/2-inch backelectret-type condensor microphone MI-1234 Nominal sensitivity level: -29 dB
Preamplifier	MI-3111 Preamplifier for microphone
Linearity range	100 dB
Measurable frequency range	10 Hz to 20 kHz (IEC, JIS)
Measurement level range	35 to 137 dB (IEC, JIS)

Intrinsic noise	27dB or less
Time weighting	FAST, SLOW, Impulse, 10 ms
Sampling interval	20.8 μ s (other than LN) 100 ms(LN)
Start mode	Manual, timer (time setting, in increment of 1 minute), trigger (can be started after a lapse of specified time [0 to 10 seconds, in increment of 1 second] after trigger detection: trigger delay function)
Display	LCD with LED backlight semitransparent (124 x 64-dot) Measurement value display by numeric and bar indicators List display and trend graph display for various kinds of calculated values Displays of date, time, measurement time, and conditions of various kinds of instruments



Fig.2.12 Noise meter (www.onosokki.co.jp/English/hp_e/products)

In this dissertation, the wireless system is used for positioning the moving robot in Chapter 5. The Zigbee (Fig.2.13) (3sZ11, System Watt) is used to emit and receive the trigger signal. The wireless receiving unit (Fig.2.14) consists of FPGA (EP4CE22F17C6N Cyclone IV, Altera) to record data and Jetson (Jetson Nano Developer Kit, Nvidia) for controlling robot and save data into a USB flash drive. The sound signal from two microphones with maximum 196 kHz sampling frequency, trigger signal from Zigbee, Inertial measurement unit (IMU, MPU9250, InvenSense), Magnetometer (HMC5883L, Honeywell), pressure sensor (MS5611-01BA, TE

Connectivity) for estimating altitude, and Thermometer (ADT7410, Analog Devices) data are recorded by the FPGA. The wireless receiving unit is fixed on the crawler robot (Fig.2.15) (TS500, Aliexpress) with 5 voltage power.

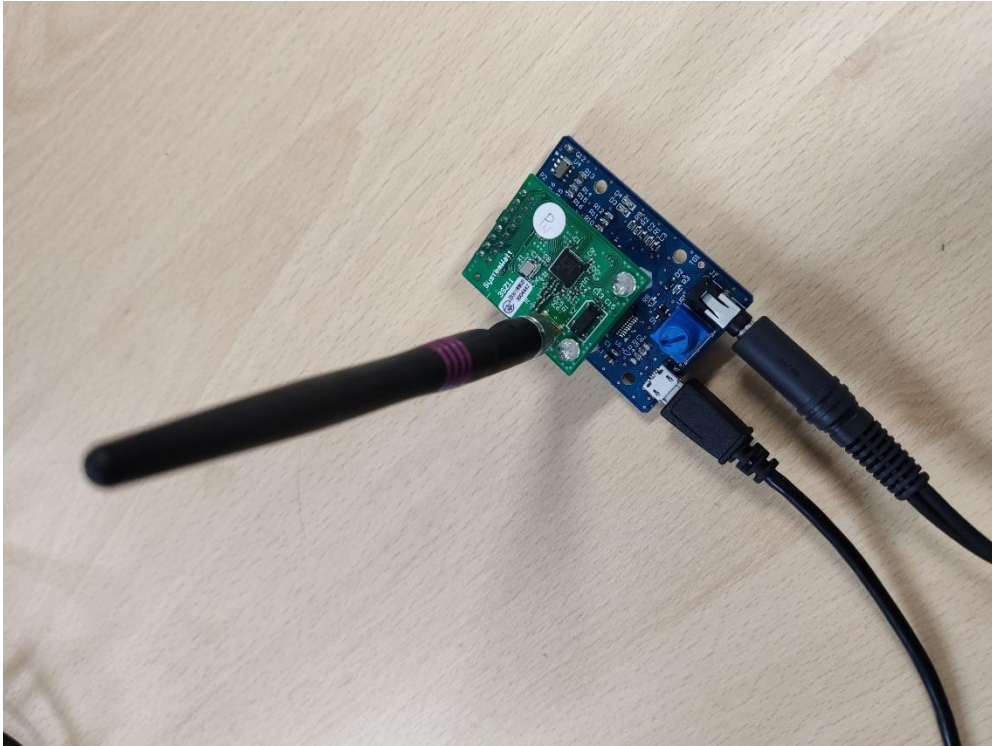


Fig.2.13 Zigbee for transmitting and receiving the trigger signal

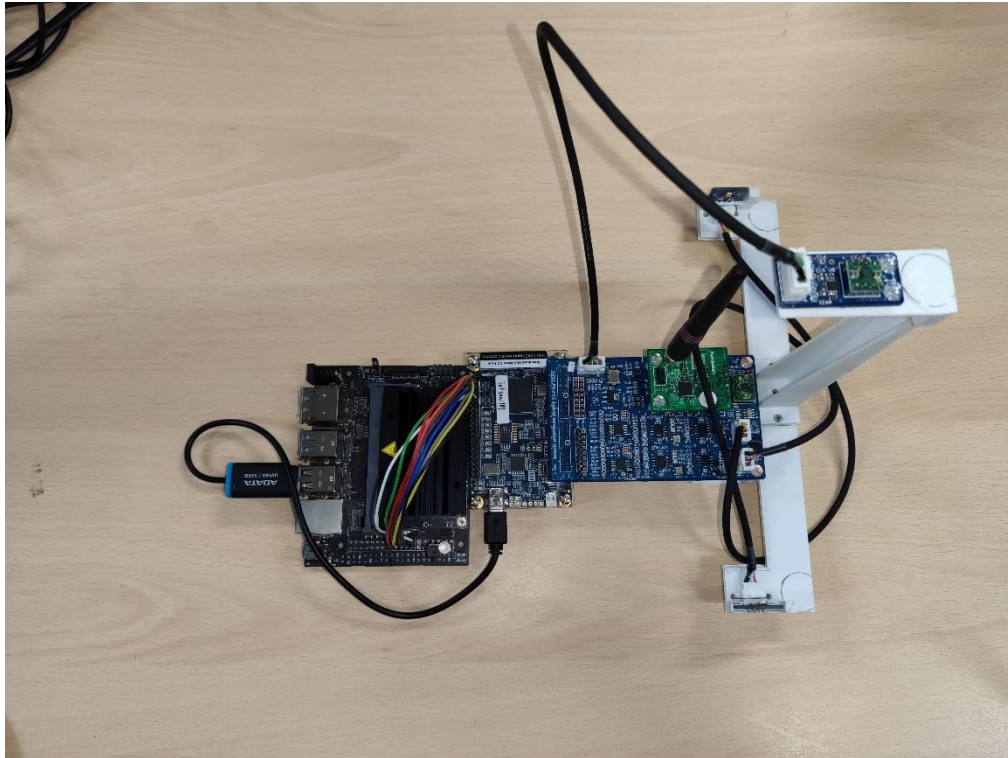


Fig.2.14 Wireless receiving unit

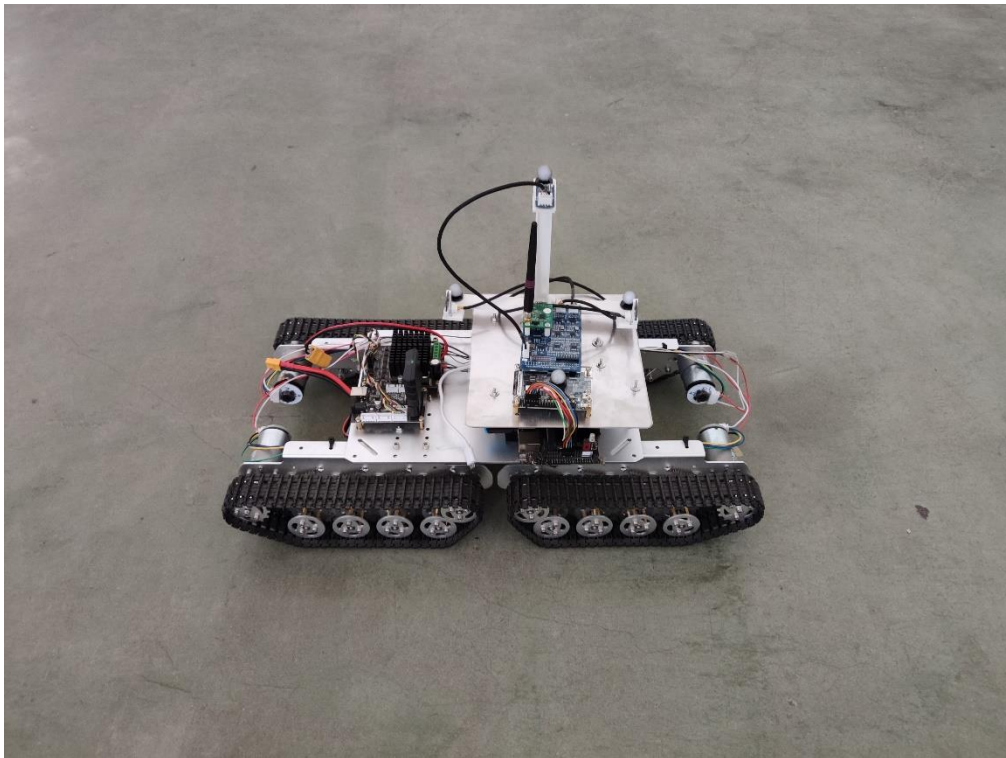


Fig.2.15 The crawler robot mounted a wireless receiving unit

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Chapter 3 *Orientation measurement system using spread spectrum sound in a greenhouse*

3.1 Background

A critical requirement for such cooperative and distributed small robots will be position and orientation data that is dynamically responsive in order to prepare motion plans. Although there are various indoor positioning techniques, we focus on a positioning and orientation system that uses spread spectrum sound due to its high accuracy and low-price tag. To date, our lab has developed a SSSLPS that can determine position within a 30 m $\times$ 30 m area to an accuracy of 20 mm (average RMSE) in the two-dimensional (2D) plane (Widodo et al., 2014). For the robot to move autonomously, though, we now need to add simultaneous orientation measurements.

Though geomagnetic direction sensors are often used for such orientation measurements, their susceptibility to a magnetic material interference, such as iron, reduces their accuracy drops to about 20° (Kondo et al., 2004). On the other hand, GPS compass measurements of orientation in indoor environments can have errors of more than 10° (Muller et al., 2006). We hypothesize that a SSSound system using two receivers to measure orientation can achieve a greater accuracy in greenhouse conditions than the above methods, while at the same time being affordable and able to be deployed on small robots.

The objective of this research is to develop and evaluate the accuracy of orientation measurement using SSSound. Two methods were developed: one based on the coordinates of the two receivers; and the other based on the receiver's coordinates and the distance to the other receiver. The accuracy of these methods in a greenhouse was

Partial results of this chapter have been published in:

Huang, Z., Fukuda, H., Wai Jacky, T.L., Zhao, X., Habaragamuwa, H., Shiigi, T., Suzuki, T., Naoshi, K., 2018. Greenhouse Based Orientation Measurement System using Spread Spectrum Sound. IFAC-PapersOnLine 51, 108–111.

Full version of this chapter has been submitted for publication

evaluated with and without deleting errors caused by the reflection of the sound signal.

3.2 Theory of orientation measurement by SSSound

Fig.3.1 shows the method 1 for orientation measurement. In the method 1, microphones 1 and 2 were respectively measured by SSSound, and a vector $\overrightarrow{P_{m1}P_{m2}}$ (red arrow) was calculated from the coordinates of the two microphones by the following equation,

$$\overrightarrow{P_{m1}P_{m2}} = P_{m2}(x_{m2}, y_{m2}, z_{m2}) - P_{m1}(x_{m1}, y_{m1}, z_{m1}) \quad (3.1)$$

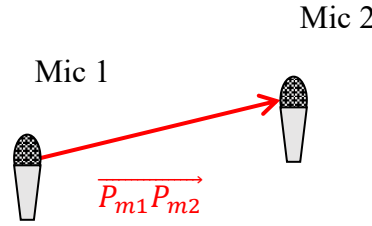


Fig.3.1 Method 1 of orientation measurement

In the method 2 (Fig.3.2), since the distance between two microphones ($|\overrightarrow{P_{m1}P_{m2}}|$) are known, the vector $\overrightarrow{P_{m1}P_{m2}}$ was calculated using the coordinates of the microphone 1 and the distance difference ($|\overrightarrow{\Delta d_j}|$) between the speakers j of the microphones 1 and 2 by the Eq.3.2.

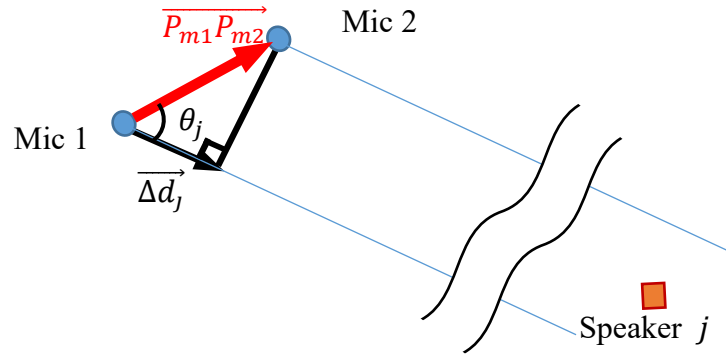


Fig.3.2 Method 2 of orientation measurement

$$\overrightarrow{\Delta d_j} \cdot \overrightarrow{P_{m1}P_{m2}} = |\overrightarrow{\Delta d_j}| |\overrightarrow{P_{m1}P_{m2}}| \cos \theta_j \quad (3.2)$$

The vector of distance difference $\overrightarrow{\Delta d_j}$ and $\cos \theta_j$ can be described as

$$\begin{aligned} \overrightarrow{\Delta d_j} &= |\overrightarrow{\Delta d_j}| \frac{\overrightarrow{P_{m1}P_{sj}}}{|\overrightarrow{P_{m1}P_{sj}}|} \\ \cos \theta_j &= \frac{|\overrightarrow{\Delta d_j}|}{|\overrightarrow{P_{m1}P_{m2}}|} \quad (d_{1j} - d_{2j} \geq 0) \\ \cos \theta_j &= -\frac{|\overrightarrow{\Delta d_j}|}{|\overrightarrow{P_{m1}P_{m2}}|} \quad (d_{1j} - d_{2j} < 0) \end{aligned} \quad (3.3)$$

The Eq. (3.2) can be simplified as:

$$\begin{aligned} \frac{\overrightarrow{P_{m1}P_{sj}}}{|\overrightarrow{P_{m1}P_{sj}}|} \cdot \overrightarrow{P_{m1}P_{m2}} &= |\overrightarrow{\Delta d_j}| \quad (d_{1j} - d_{2j} \geq 0) \\ \frac{\overrightarrow{P_{m1}P_{sj}}}{|\overrightarrow{P_{m1}P_{sj}}|} \cdot \overrightarrow{P_{m1}P_{m2}} &= -|\overrightarrow{\Delta d_j}| \quad (d_{1j} - d_{2j} < 0) \end{aligned} \quad (3.4)$$

Four speakers were used to calculate the vector $\overrightarrow{P_{m1}P_{m2}}$, so the vector can be derived as,

$$\overrightarrow{P_{m1}P_{m2}} = (\mathbf{A}^T \cdot \mathbf{A})^{-1} \cdot \mathbf{A}^T \begin{bmatrix} |\overrightarrow{\Delta d_1}| \\ |\overrightarrow{\Delta d_2}| \\ |\overrightarrow{\Delta d_3}| \\ |\overrightarrow{\Delta d_4}| \end{bmatrix} \quad (3.5)$$

where,

$$\mathbf{A} = \begin{bmatrix} \overrightarrow{P_{m1}P_{s1}} \\ |\overrightarrow{P_{m1}P_{s1}}| \\ \overrightarrow{P_{m1}P_{s2}} \\ |\overrightarrow{P_{m1}P_{s2}}| \\ \overrightarrow{P_{m1}P_{s3}} \\ |\overrightarrow{P_{m1}P_{s3}}| \\ \overrightarrow{P_{m1}P_{s4}} \\ |\overrightarrow{P_{m1}P_{s4}}| \end{bmatrix} = \begin{bmatrix} \frac{x_{s1} - x_{m1}}{|\overrightarrow{P_{m1}P_{s1}}|} & \frac{y_{s1} - y_{m1}}{|\overrightarrow{P_{m1}P_{s1}}|} & \frac{z_{s1} - z_{m1}}{|\overrightarrow{P_{m1}P_{s1}}|} \\ \frac{x_{s2} - x_{m1}}{|\overrightarrow{P_{m1}P_{s2}}|} & \frac{y_{s2} - y_{m1}}{|\overrightarrow{P_{m1}P_{s2}}|} & \frac{z_{s2} - z_{m1}}{|\overrightarrow{P_{m1}P_{s2}}|} \\ \frac{x_{s3} - x_{m1}}{|\overrightarrow{P_{m1}P_{s3}}|} & \frac{y_{s3} - y_{m1}}{|\overrightarrow{P_{m1}P_{s3}}|} & \frac{z_{s3} - z_{m1}}{|\overrightarrow{P_{m1}P_{s3}}|} \\ \frac{x_{s4} - x_{m1}}{|\overrightarrow{P_{m1}P_{s4}}|} & \frac{y_{s4} - y_{m1}}{|\overrightarrow{P_{m1}P_{s4}}|} & \frac{z_{s4} - z_{m1}}{|\overrightarrow{P_{m1}P_{s4}}|} \end{bmatrix}$$

3.3 Experiment in a greenhouse

We conducted experiments at the greenhouse at the Experimental Farm of Graduate School of Agriculture in Kyoto University in Kizugawa City, Kyoto Prefecture. Speakers with known coordinates were installed at the four corners of a 6 m $\times$ 15 m green house, and the microphones were installed in the area surrounded by the speakers. Measuring positions are the red points in Fig.3.3 from No. 1 to 28 at 50 cm interval. Two microphones were installed so that the vector of these two microphones can be calculated and used for evaluating the orientation. Here these two microphones are aligned in the x axis direction. Also, the distance between the microphones was set to 20 cm, and the midpoint between the microphones was set to be the red point in Fig.3.3. Besides, both the microphones and the speakers were installed at a height of 50 cm from the ground.

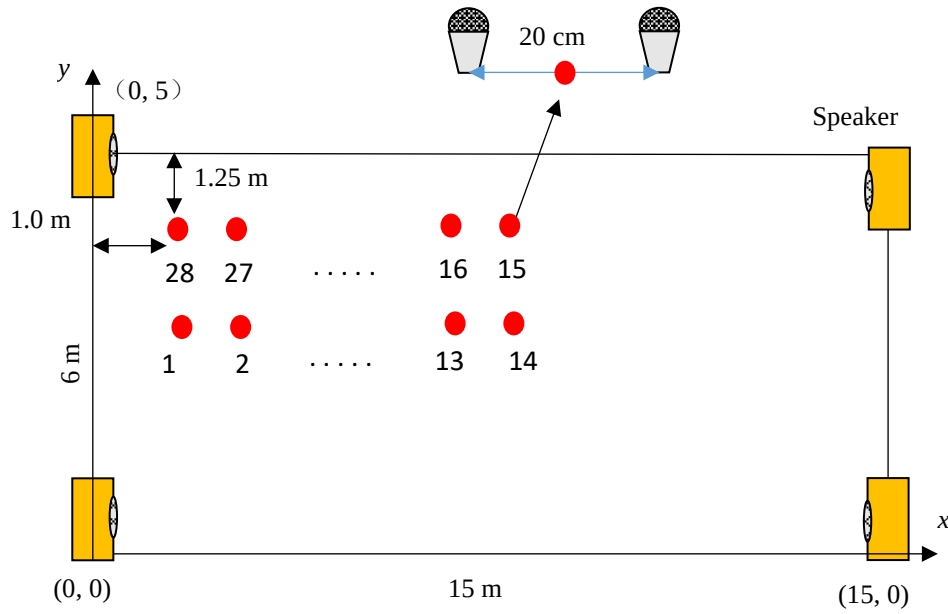


Fig.3.3 Experimental settings and measured positions

The amplifiers and audio interface were used to generate a sound signal from the speakers, and the sound level of the emitted sound adjusted at 83 dB. The temperature at speakers and microphones were monitored by a wireless thermometer. The properties of these devices are summarized in Table 3.1.

Table 3.1 Devices functions and properties

Device	Specification
Amplifier	Kama Bay Amp Rev. B, Scythe Inc.
Audio interface	OCTA-CAPTURE UA-1010, Roland
Speaker	FT28D, Fostex Company
Microphone	SPM 0404 UD 5, Knowles Electronics
Thermometer	3670 Hioki, accuracy 0.1°C

The TDMA signals (Fig.3.4) are used in this experiment. The interval between

each channel is 250 ms. The length of SSSound is 75 ms. A total station (Sokkia-SRX5XT32T-11) was used to get the position of these two microphones with 0.1 mm accuracy. Then the accurate orientation was calculated by the accurate position of these two microphones using the same method as Eq.3.1.

Orientation was measured 60 times at each position by these two methods. The orientation accuracy was evaluated by the RMSE comparing with the vector measured by total station.

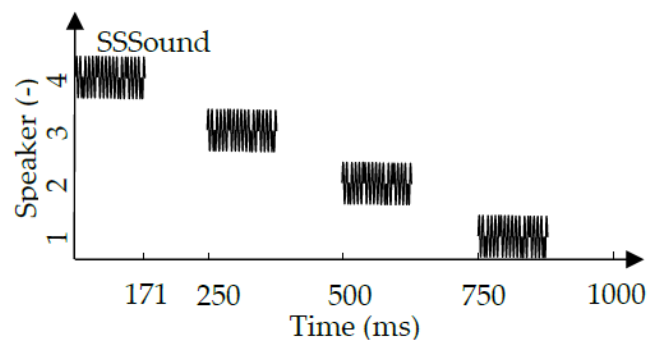


Fig.3.4 TDMA signals

3.3 Results and discussion

Fig.3.5 shows the orientation measurement result by SSSound with two methods. The average error of all measurements was 28.9° in method 1 and 23° in method 2. The average orientation accuracy by these two methods can reach 10 degree almost half case (12 out of 28). For the most case (22 out of 28), the method 2 has better average accuracy than method 1. But there is big error bar at every position, which stands for the instability for some reason. This instability may limit the application of SSSound for orientation measurement.

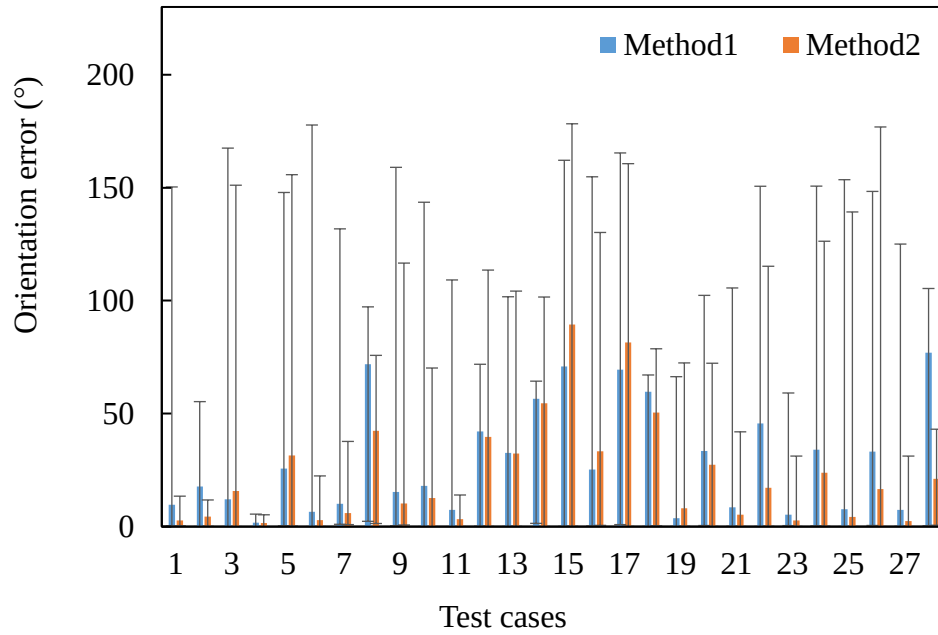
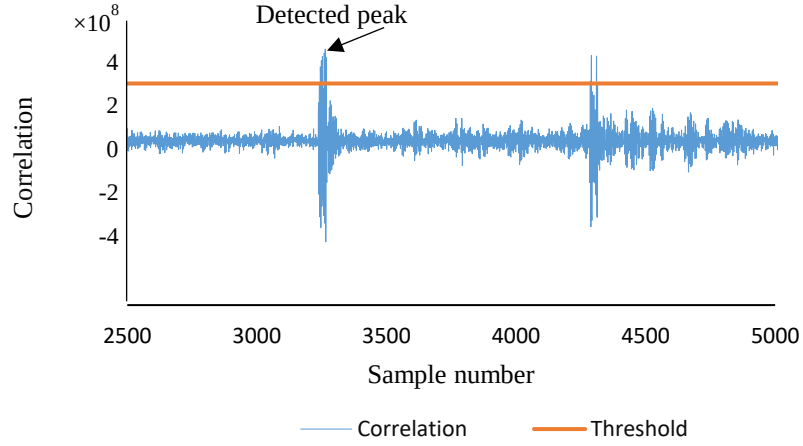
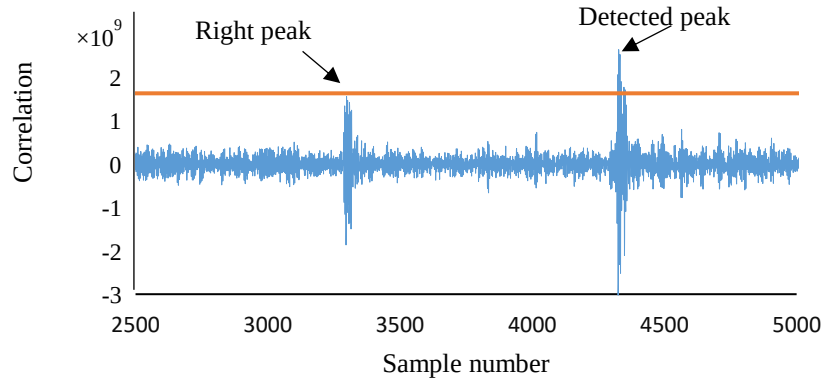


Fig.3.5 Original results of measurements at position No. 1~28

The orientation measurement is based on the positioning system and positioning system can be affected by the distance measurement by SSSound, so the reason of the big error can be analyzed by checking the cross-correlation value. Fig.3.6 (a) shows a successful example with a right detected peak. The orientation accuracy of this example is 4°. The wrong peak (sample number 4336) behind the right peak (sample number 3304) was detected at another example (Fig.3.6 (b)) at the same position.



(a)



(b)

Fig.3.6 The success (a) and failure (b) example of detected peak

The error of distance measurement can be calculated by using the difference of these two peaks number as time difference ($(4336-3304)/96000 = 0.0175$ s). Then the distance difference caused by the reflection can be calculated by multiplying sound velocity ($0.0175 \times 340 \approx 3.6$ m). This example is the distance data from microphone 2 to speaker 2, which is around 1.5 m close to the greenhouse wall. The distance difference (3.6 m) of reflected and direct wave is almost 2 times as the distance (1.5 m) from speaker 2 to the greenhouse wall, so the error is caused by the sound reflection

from greenhouse wall (Fig.3.7).

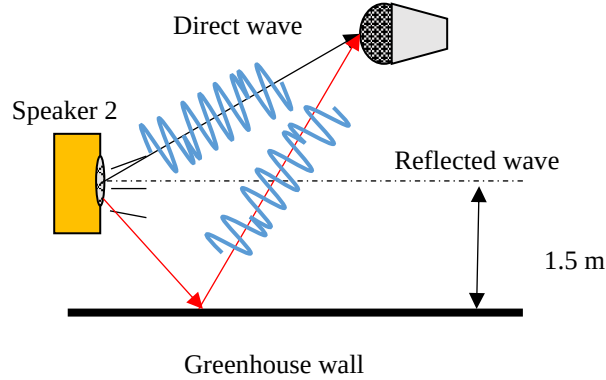


Fig.3.7 Reflected wave from greenhouse wall

Since the threshold uses the maximum value, average absolute value and standard deviation of cross-correlation, the threshold will be higher than the direct wave. The threshold is improved in the following equation,

$$c_{th} = C_{ave} + 4\sigma_{corr} \quad (3.6)$$

The result of positioning error with new threshold is shown in Fig.3.8. With the new threshold, the direct sound signal can be successfully detected. The average 2D positioning error is 21.5mm. This accuracy is similar to our previous experiment (Widodo et al., 2014) and can meet the most positioning requirements for the greenhouse robots.

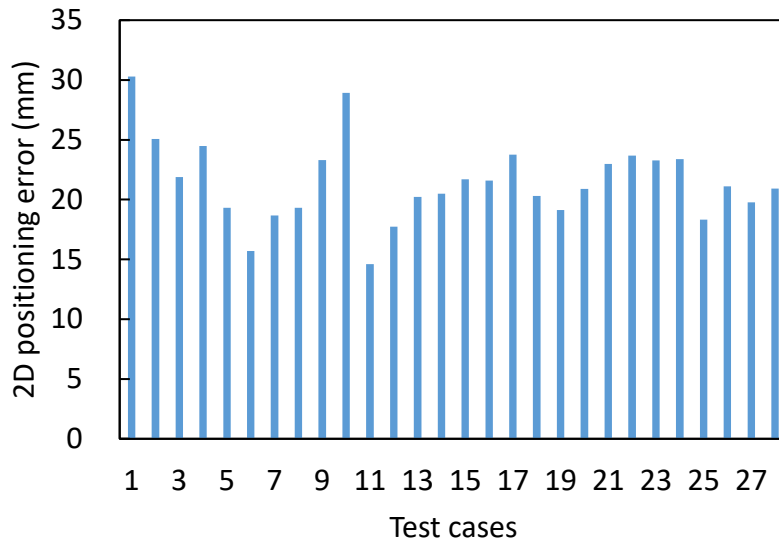


Fig.3.8 Positioning error using the new threshold

The average orientation error of method 1 (M1) and method 2 (M2) are 3.41° and 1.55° . In most cases (25 out of 28), method 2 has better accuracy than method 1, as shown in Fig.3.9. By checking the correlation value at position No.10, the reason of the error bar in Fig.3.9 was analyzed.

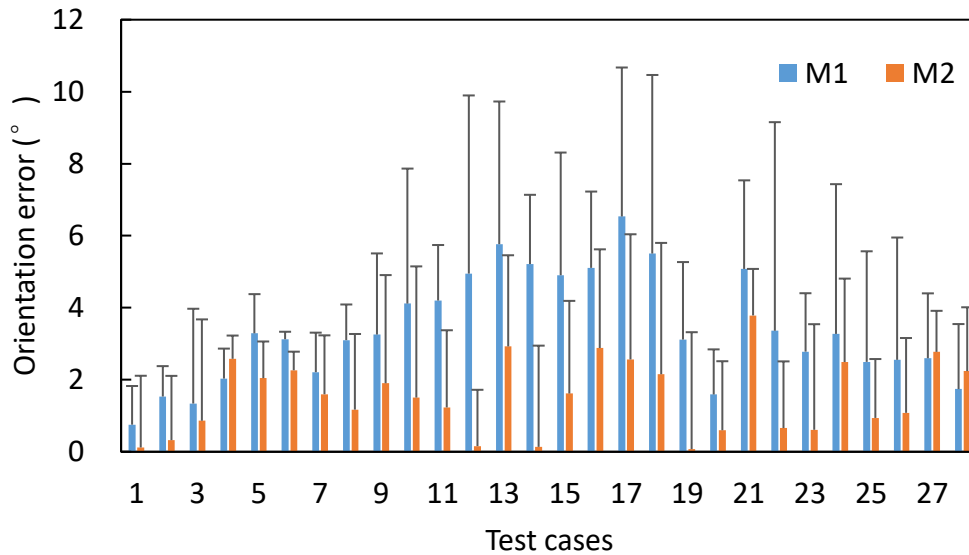


Fig.3.9 Orientation error

Fig.3.10 shows the examples of correlation of one distance measurement. The orientation of these two examples are 4.2° and 8.7° correspondingly. The system judges the peak over the threshold as the arrival time of SSSound signal. In Fig.3.10 (a), the arrival peak is recognized as 3202. While in Fig.3.10 (b), the arrival peak is judged as 3207. For one arrival signal, over the threshold there should have three peaks, while interference by the background noise can change the shape of these three peaks. Sometimes only the central peak over threshold was recognized (Fig.3.10 (a)). If there have two near peaks, the second peak will be recognized the wrong peak with 4 phase difference (Fig.3.10 (b)). This 4 phase difference will lead to 15 mm error. Since two microphones in total have 8 distance to four speakers, the distance error of different speaker and microphone pairs lead to 1.55° orientation error of method 2.

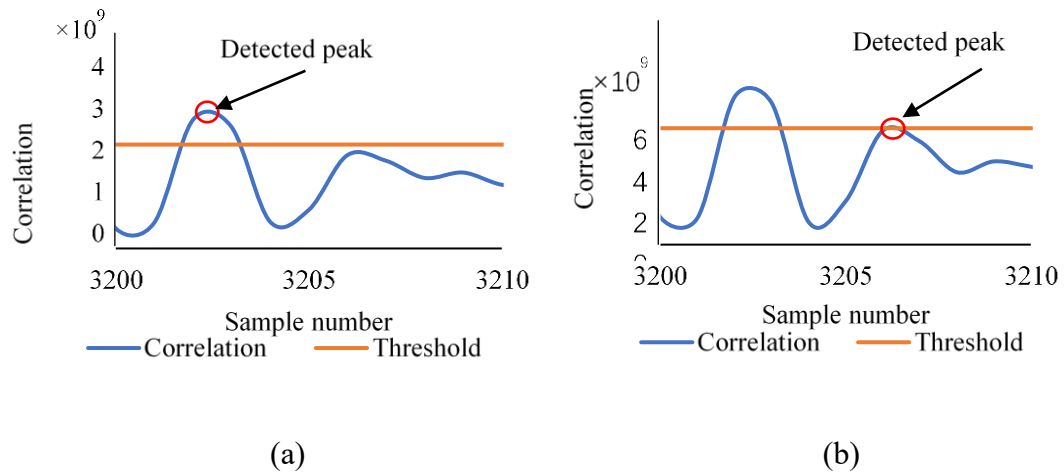


Fig.3.10 The examples of detected peak at 3202 (a) and 3207 (b)

3.4 Conclusions

Using two novel SSSound based positioning and orientation systems without any sound signal reflection error compensation, their accuracy was found to be only 23° . When the reflection error was removed by the new threshold, the average accuracy of the orientation measurements increased to 3.41° and 1.55° , respectively for the two

methods, which meets the requirements of most agricultural applications. Comparing the two methods, method 2 has better accuracy than method 1. Given that temperatures in a greenhouse can also vary considerably, the effects of temperature need to be considered in the future research.

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Chapter 4 *A noise tolerant spread spectrum sound-based local positioning system for operating a quadcopter in a greenhouse*

4.1 Background

Drones are beginning to play an important role in precision agriculture, as they provide farmers with rapid and semi-autonomous data about the crops. The benefits of using drone implementation have been identified (Simon et al., 2018) as: reduced measurement and data collection time, precision of measured data, increased yields, decreased costs of fertilizers and pesticides, and so on. To date, most applications have focused on outdoor operations, some applications are already commercialized, such as monitoring the health of crops by using Normalized Differential Vegetation Index (NDVI) in open fields (Reinecke and Prinsloo, 2017) and greenhouses (Calero et al., 2018), detecting (Y. Huang et al., 2018) and mapping (Barrero et al., 2016) weeds, surveying the agricultural field (Christiansen et al., 2017), and spraying pesticides and fertilizers (Faical et al., 2017). Quadcopters, typically small drones with four motors, with less air turbulence have attracted the interest of researchers for measuring environmental variables (Roldan et al., 2015) in a greenhouse, such as temperature, humidity, CO₂ concentration, and so on. Flying quadcopters in greenhouses can also accomplish pollination and yield estimation (Oppenheim et al., 2017). However, for further automated quadcopter operations in greenhouses, a robust positioning system is a critical requirement.

Unfortunately, the ubiquitous Global Navigation Satellite System (GNSS) cannot be used as a positioning system in greenhouses due to large indoor positioning errors (Gu et al., 2009). Indoor positioning is an important part of Internet of Things (IoT) and plays an important role in improving most services in IoT (Rezazadeh et al., 2018a,

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2018b). Moreover, many of the other commercialized indoor positioning systems use Ultra-Wide Band (UWB) signals that only have a 100 mm accuracy (Mazhar et al., 2017), and can interfere with wireless systems in Industrial Scientific Medical and Mobile cellular bands (Nikookar and Prasad, 2009). Other research has used a machine vision system for localizing the quadcopter with color markers on the motors (Achtelik et al., 2009). Even this system only has a 128 mm positioning accuracy due to camera resolution and limited coverage, due to the field of view. On the other hand, sound-based positioning systems offer an attractive alternative with high accuracy and low cost.

The objectives of this research are first, to document the acoustic noise emitted from a model quadcopter operated at various thrust levels and using different propellers. Then, with reference to the properties of this noise, improve the noise tolerance of the SSSound signals. Finally, the performance of this SSSLPS mounted on a quadcopter in a greenhouse was evaluated.

4.2 Materials and methods

4.2.1 Acoustic noise measurement

The setup for measuring the noise spectrum is shown in Fig.4.1. The quadcopter model consists of an Electronic speed control (ESC, 50A, KYWALKER), brushless motors (FC4250-6T KV720, FSD), and power supply (HRC44174, HiTEC). Three kinds of carbon propellers, models 8×3.8 , 10×4.5 , and 12×4.5 (by GEMFAN), with diameters of 20.5 cm, 25.5 cm, and 30.5 cm, respectively, were used in the experiments to document the acoustic noise emitted from the quadcopter. The Arduino (UNO REV3, Arduino) was used to control the ESC using Pulse Width Modulation (PWM) signals. The quadcopter was fixed on a stand with a thrust meter (Tahmazo, OK Model,

accuracy 5 g). A tachometer (HT-5100 Ono Sokki, accuracy ± 1 r/min) and a reflective board attached on the motor were used to measure the rotational speed (Revolutions Per Minute (RPM)) of the motor. The height of the quadcopter and the microphone (ECM-100N, Sony, frequency response ± 3 dB) was set at 1.5 m above the ground.

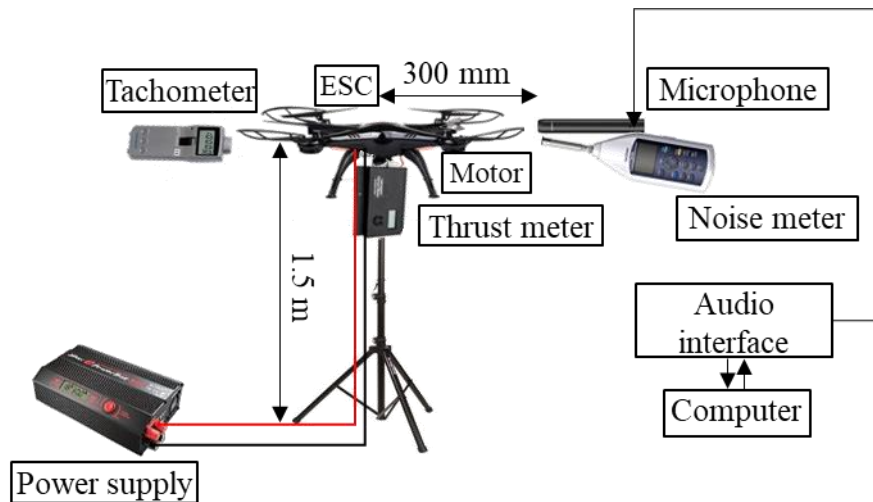


Fig.4.1. Setup for measuring the noise spectrum

The SSSound signal covers the ultrasonic range, so a noise meter (LA-4440, Ono Sokki, frequency response ± 1 dB) and microphone were used to evaluate the frequency spectrum of the acoustic noise emitted from the quadcopter. The microphone was connected to the computer by an audio interface (OCTA-CAPTURE UA-1010, Roland) with a constant gain value.

The relationship between the sound pressure level (dB) measured by the noise meter and the signal recorded by microphone can be expressed by the following equation:

$$L_{noise\ meter} = 10 \log_{10} \frac{p_m^2}{p_0^2}$$

$$p_m = \sqrt{\frac{\sum (Gain \times signal)^2}{N}} \quad (4.1)$$

$$Gain = \sqrt{\frac{p_0^2 \times N}{\sum (signal)^2}} \times 10^{\frac{L_{noise\ meter}}{10}}$$

where, $L_{noise\ meter}$ is the sound pressure level measured by the noise meter, p_m is the sound pressure measured by the microphone, p_0 is the reference sound pressure (2×10^{-5} Pa), $Gain$ is the system gain, and $signal$ is the received signal.

The noise meter measures sound pressure level from 10 to 20 kHz, so the $Gain$ in Eq4.1 can be calculated using the received signal with the same frequency range as the noise meter. With a 96kHz sampling frequency and a Band Pass Filter (BPF) for the received signal, the sound pressure level can be measured over the above frequency range. The microphone was set at 300 mm from the center of the quadcopter. The thrust of the quadcopter was set to 4.91N, 9.73 N, and 14.72N (± 0.45 N). A 5 s sound signal was recorded at each condition under the stable thrust.

4.2.2. Noise tolerance against the quadcopter

Three groups of SSSound signals were generated, taking into consideration that the period of the M-sequence (M_{length}), the frequency of the carrier wave, and chip rate could affect the noise tolerance of the SSSound. The properties of these signals are shown in Table 4.1.

Table 4.1. SSSound pairs for comparison.

Group	M_{length}	f_c (kHz)	f_{chip} (kcps)
I	1023	20, 24, 28, 32	4
II	127, 255, 511, 1023, 2047	24	12
III	1023	24	4, 6, 12, 16, 24

The strength of SSSound, in respect to the noise, is described as Signal to Noise ratio of correlation (SNR_{corr}) (Huang et al., 2017) by the following equation:

$$SNR_{corr} = \frac{C_{peak}}{C_{absave}} \quad (4.2)$$

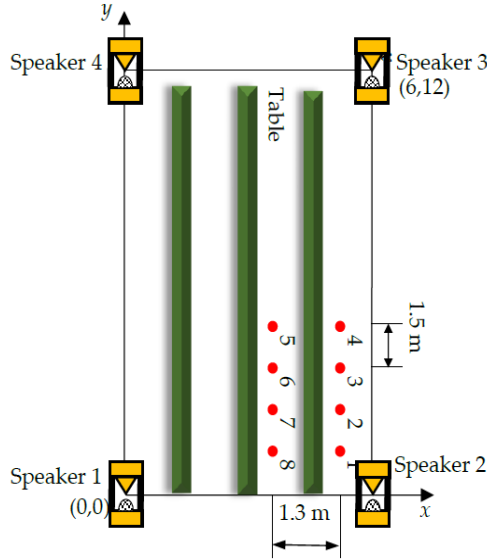
where, C_{peak} is the correlation value at the received time of the SSSound. C_{absave} is the average absolute correlation value, except in the 48 samples peak region, which is the maximum peak width of the auto-correlation. The larger the mean SNR_{corr} value, the larger the noise tolerance. Normally, the arrival time of the sound signal cannot be detected when the SNR_{corr} value is smaller than 7.

In addition to the experimental setup shown in Fig.4.1, a speaker (FT28D, Fostex Company), connected to the audio interface by an amplifier (Kama Bay Amp Rev. B, Scythe Inc.), was setup to emit the SSSound. The 1 kHz HPF was connected to the speaker. The distance between the speaker and the microphone was set at 1 m, at the same height of 1.5 m. The sound pressure level of the emitted SSSound was adjusted to 95 dB, measured 100 mm from the speaker using white noise. The thrust of the quadcopter was set at 9.73 ± 0.68 N. With the operating quadcopter fixed on the stand, the SNR_{corr} of each signal was measured 50 times for the three types of propellers.

4.2.3. Positioning experiment in the greenhouse with quadcopter noise

To evaluate the effect on the SSSLPS of the quadcopter emitted noise, an experiment was conducted in an affiliated greenhouse of Experimental Farm of Graduate School of Agriculture in Kyoto University in Kizugawa city. The coverage area of the experiment was set as 12×6 m, given the possible limited range of SSSound in the presence of quadcopter noise. Fig.4.2 shows the setup in the greenhouse. There were empty raised rockwool beds on bare soil in the greenhouse. The four speakers were set at each of the corners, and the quadcopter was sequentially set at each red point shown in Fig.4.2(a). The microphone was attached 30 cm from the center of the quadcopter. The speakers and microphone height were set at 150 cm. A commercial omnidirectional microphone (SPM0404UD5, Knowles Electronics) was used in this experiment. The temperature of the speakers and microphone were monitored using wireless thermometers (3670 Hioki, accuracy 0.1°C) in order to estimate sound velocity for distance measurements. The temperature during this experiment ranged from 26.4 to 37.3°C . This research focuses on noise tolerance in the presence of quadcopter acoustic noise, so the quadcopter was fixed on a stand (Fig.4.1). The offset, t_{delay} , was calibrated as 0.036 ms for the four speakers. The position of the microphone, P_j , was measured 50 times at each red point in Fig.4.2(a) by the SSSound system, with the quadcopter running at a thrust of 9.75 ± 0.58 N using propeller model 10×4.5 . The positioning accuracy of the SSSLPS was evaluated in comparison to the position, P_{ts} , measured by the total station (SRX5XT32T-11, Sokkia, accuracy $1.5 + 2\text{ppm} \times \text{measurement distance mm}$). The RMSE of position, $\text{Positioning}_{\text{RMSE}}$, at each position is calculated by the following equation:

$$Positioning_{RMSE} = \sqrt{\frac{1}{50} \sum_{j=1}^{50} (P_j - P_{ts})^2} \quad (4.3)$$



(a)



(b)

Fig.4.2. Experimental setup (a) and view (b) in the greenhouse

Both TDMA and Frequency Division Multiple Access (FDMA) signals were evaluated in the experiment. The TDMA signal used was based on the SSSound signal generated by a 2047 length M-sequence, 24 kHz carrier wave, and 12 kcps chip rate. The length of the SSSound was 171 ms. Channels 1 to 4 were the SSSound channels of the speakers, as shown in Fig.4.3(a) The interval between the speakers was set at 0.25 s, so one cycle of the TDMA signal was 1 s. The frequency-domain of the FDMA signal is shown in Fig.4.3(b) The four speakers produced 17, 26, 35, and 44 kHz carrier waves in the corresponding channels with a 4 kcps chip rate and a 1023 length M-sequence. The length of each SSSound signal in the FDMA channel was 256 ms, which was much longer than the 171 ms length signal in the TDMA channel. The received signal, N , of

TDMA and FDMA was sampled 24,000 and 48,000 times for each channel, respectively. At each measured position, the TDMA and FDMA based SSSound was measured with and without the operating quadcopter to compare the effect of quadcopter emitted noise.

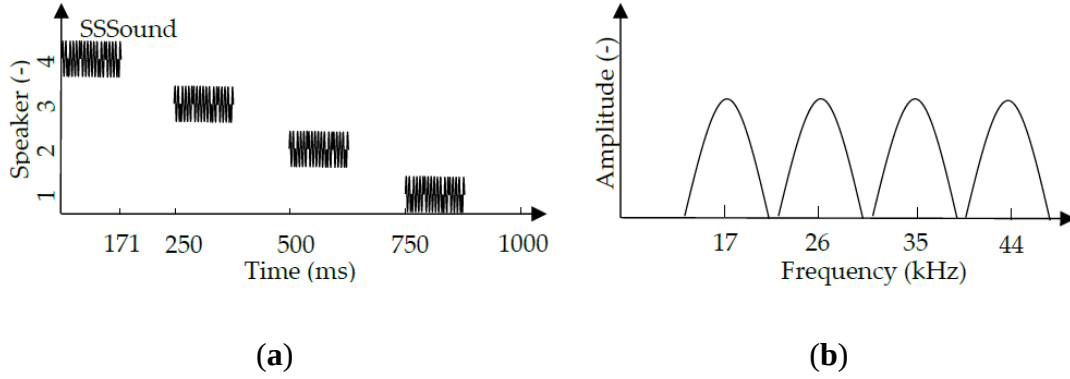
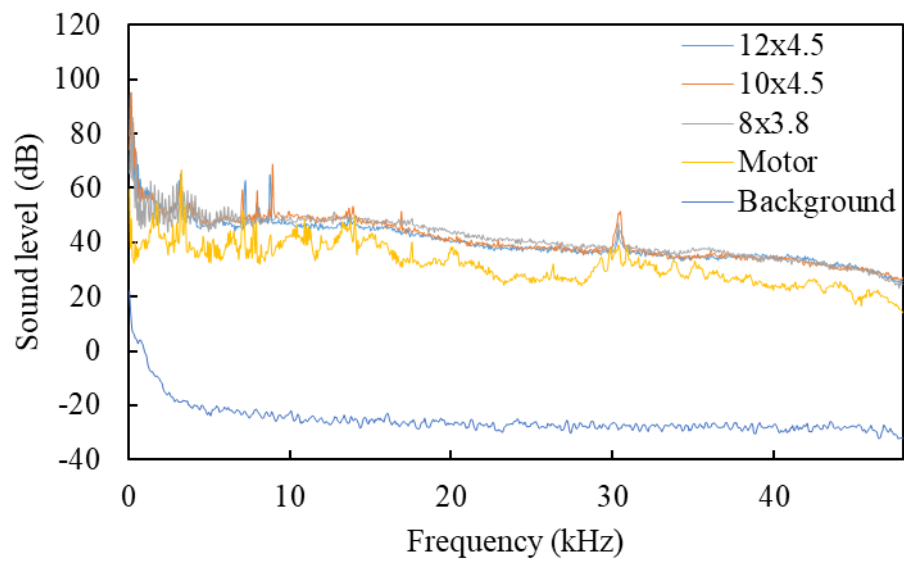


Fig.4.3. Time-division Multiple Access (TDMA) (a) and Frequency-division Multiple Access (FDMA) (b) signal

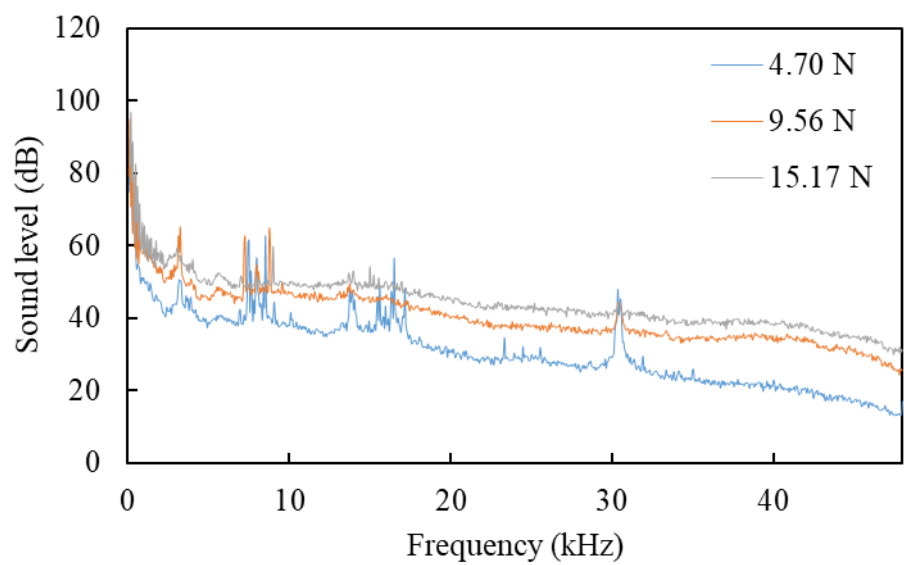
4.3 Results and discussion

4.3.1. Acoustic noise of the quadcopter

Fig.4.4(a) shows the frequency spectrum of the acoustic noise emitted from the quadcopter with three different propeller sizes, where the noise is from the motors at 4013 rpm and background noise. The rpm of the models 80×3.8 , 11×4.7 , and 12×4.5 were 3524, 4210, and 8356 rpm, respectively. Based on previous acoustic noise classification from quadcopters (Intaratep et al., 2016), the acoustic noise in this experiment was classified into low frequency range (0–10 kHz) and high frequency range (>10 kHz). In the low frequency range, shaft rate, blade passing frequency, rotor self-noise, and their harmonics could be observed.



(a)



(b)

Fig.4.4. Acoustic noise spectrum of the quadcopter noise at 9.73 N thrust (a) and spectrum change with thrust using propeller model 10×4.5 (b)

The difference of the noise spectrum with the three propellers model mainly exists in the low frequency because of the different motor RPM. Other research (Widodo, 2013) has pointed out that acoustic noise from agricultural machinery, such as mower engines, hand movers, and combine harvesters, are generally in the low frequency range. Thus, to avoid noise interference from the quadcopter or other agricultural machineries, the SSSound signal should be in a higher frequency range. In this research, the minimal SSSound frequency was set as 10 kHz. Acoustic noise in high frequencies above 10 kHz is described as broadband noise, which causes turbulent flow over the blades; something that was also observed in previous research (Intaratep et al., 2016; Pereda Albarran et al., 2019).

Noise around 30.5 kHz is presumably from laminar boundary layer vortex shedding (Intaratep et al., 2016). This noise is coupled to acoustically excited feedback loops, generated between the trailing edge and instability waves upstream of the trailing edge (Jianu et al., 2012). The noise spectrum changed with thrust when using the 11×4.7 propeller, as shown in Fig.4.4(b). As the thrust increased from 4.70 to 15.17 N, broadband noise at higher frequencies increased. Thus, the noise generated by the quadcopter was considered to be broadband noise, compared to that of the SSSound signal used in this research.

4.3.2. Noise tolerance against the quadcopter

Fig.4.5 shows changes in noise tolerance with the carrier frequency. The SNR_{corr} value fluctuated around 13.9 with the four tested carrier frequencies. The coverage of these signals was 8 to 44 kHz. This frequency range includes vortex shedding around 30.5 kHz, so the SNR_{corr} value at 28 kHz was slightly lower, around 9.3, than the SNR_{corr} value at other carrier frequencies. The standard deviation was around 7, associated with the three different propeller types tested. The average SNR_{corr} value of the four carrier

waves was 118.7. Based on the noise spectrum emitted from the quadcopter, these carrier frequencies could be affected by noise at 30.5 kHz, and its effect on the SNR_{corr} value was around 7.8% ($=9.3/118.7 \times 100\%$).

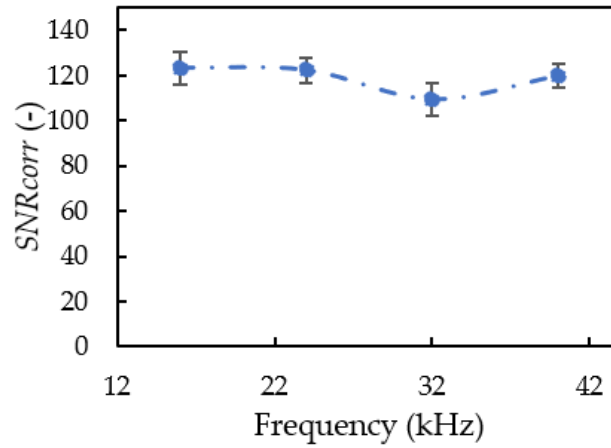


Fig.4.5. The effect of carrier wave changes to the noise tolerance

The longer M-sequence lengths and shorter chip rates trialed had larger SNR_{corr} values (Fig.4.6). By doubling the length of the M-sequence, the SNR_{corr} value increased by about 20. The M-sequence is multiplied by the sine wave, so the correlation value increases as the M-sequence length increases. As the chip rate increased, the noise tolerance decreased. A chip rate of 24 kcps had the largest decrease in noise tolerance, because the 24 kHz carrier wave and 24 kcps chip rate compose the SSSound signal with 48 kHz broadband frequency that covered the quadcopter noise in the low frequency.

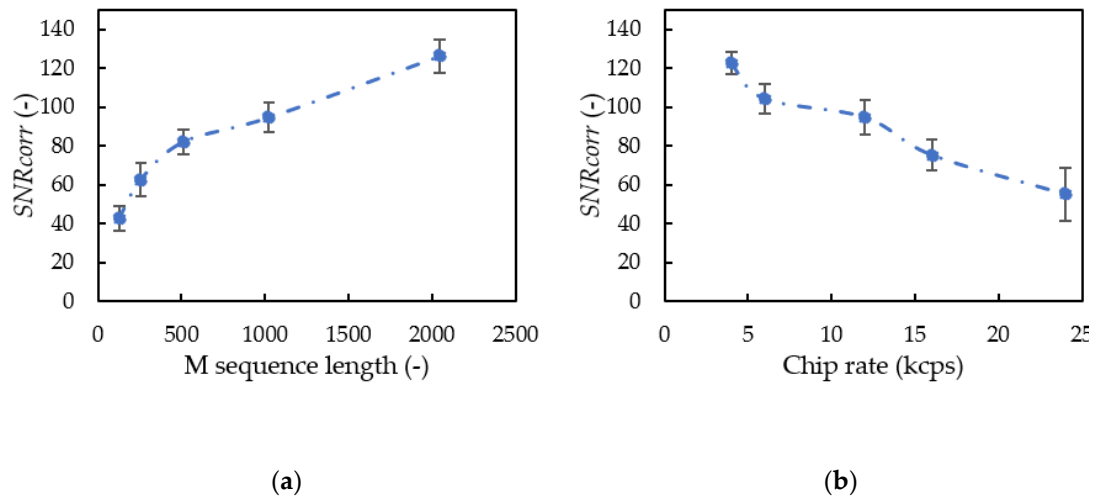


Fig.4.6. Noise tolerance change with M-sequence length (a) and chip rate (b)

The length of the SSSound signal (L_S , unit s) can be calculated by the following equation:

$$L_S = \frac{M_{length}}{f_{chip}} \quad (4.4)$$

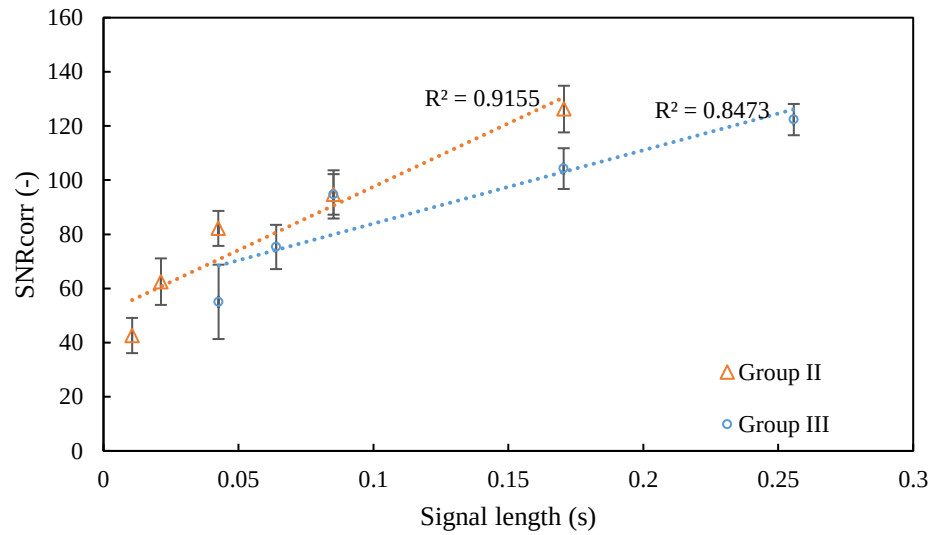


Fig.4.7. Signal length with the noise tolerance

A smaller chip rate and longer M-sequence length would have better noise

tolerance. Fig.4.7 shows the correlation coefficient between signal length and the SNR_{corr} value. The correlation coefficient, R^2 , between signal length and SNR_{corr} value was larger than 0.84 for both M-sequence length and chip rate. A shorter chip rate means more sine wave was coded into the M-sequence, while the sine wave itself didn't contribute much to noise tolerance. For example, the typical SSSound properties are 1023 M-sequence length, 24 kHz carrier wave and 12 kcps chip rate. One M-sequence is coded by two sine waves for the typical SSSound. The SNR_{corr} value of SSSound using 21 kHz carrier wave and 6 kcps chip rate is around 10% ($=9.5/94.7 \times 100$) larger than the typical SSSound, while this signal codes four sine waves on one M-sequence. The slope in Fig.4.7 of the M-sequence length is larger than that for chip rate, so increasing the M-sequence length is an effective means to increase noise tolerance of the SSSound system. Meanwhile, with longer signal length the processing time of the CPU is longer.

4.3.3. Positioning results in a greenhouse with quadcopter noise

The RMSE of the positioning error for both TDMA and FDMA signals when the quadcopter was operating and without quadcopter noise is shown in Fig.4.8. The RMSE of the 2D positioning of the TDMA modulation with and without quadcopter noise, was 15.9 mm and 23.2 mm, respectively. The RMSE of FDMA modulation with and without noise, was 16.0 mm and 31.6 mm, respectively. The error bars are the standard deviation of 50 measurements of each signal. Positions 1, 2, and 8 have errors that are larger than for the other positions; presumably, because these three positions are around 45 mm distance error from speaker 4 to the microphone.

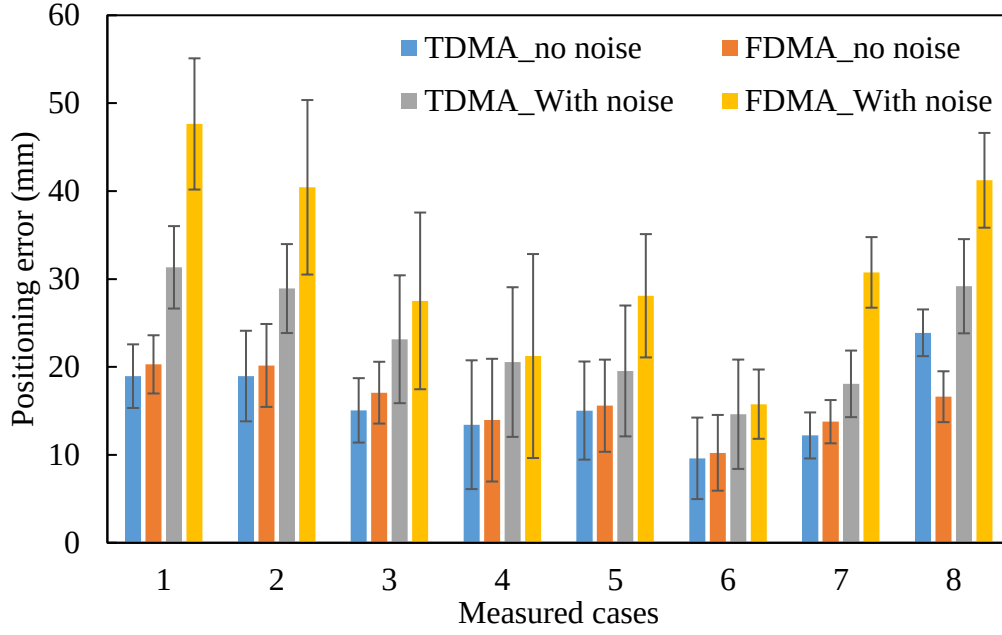


Fig.4.8. Positioning error

In the presence of quadcopter noise, the positioning errors and error bars for both the TDMA and FDMA modulations increased. Fig.4.9 shows the correlation between the TDMA and FDMA signals at position 1, from speaker 4 to the microphone. The red points in Fig.4.9 indicate the detected peak using the threshold method. The width of the peak region for the TDMA and FDMA signals were 16 and 48 sample numbers. Fig.4.9(a) is the correlation for the TDMA signal with no quadcopter noise. The second peak over the threshold was the arrival time of the SSSound signal. With the interference of the quadcopter noise, the correlation peak changes from Fig.4.9(a) to Fig.4.9(b) and the wrong peak was detected, so the distance measurement error increased and lead to the positioning error increase. The average absolute correlation and standard deviation of the correlation increased, so the threshold in Fig.4.9(b) is larger than the threshold without the quadcopter noise (Fig.4.9(a)). At this position, the positioning error of SSSLPS using TDMA signal were 18.9 mm without the quadcopter noise, and 31.3 mm with the quadcopter noise. For the FDMA signals with (Fig.4.9(d)) and without (Fig.4.9(c)) the quadcopter noise, the larger distance measurement error

appears because the FDMA has a greater width of the peak region, and the correct peak is difficult to be detected. The positioning accuracy can be affected by sampling frequency (Shiigi et al., 2010), the error of correlation peak, Dilution of precision (DOP) (Shiigi et al., 2017), and the error of sound velocity measurement (Shiigi et al., 2017). The system settings can generate geomatic distribution of positioning error, while it is difficult to avoid due to the rectangular structure of the greenhouse. Without the quadcopter noise, the correct correlation peak of both TDMA and FDMA signals can be detected. In this experiment, the error of sound velocity estimation contributes to the positioning error without the quadcopter noise. The correct peak is difficult to be detected when there was interference with the quadcopter noise.

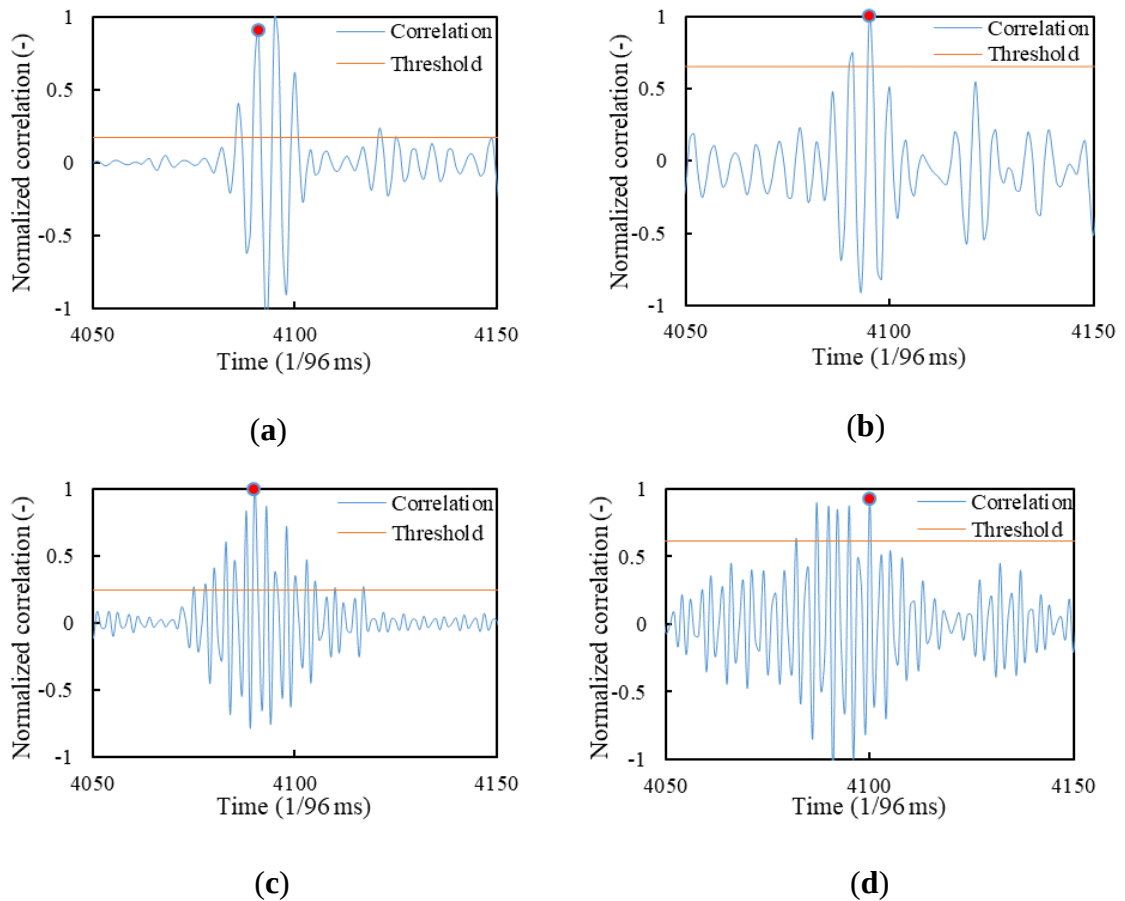
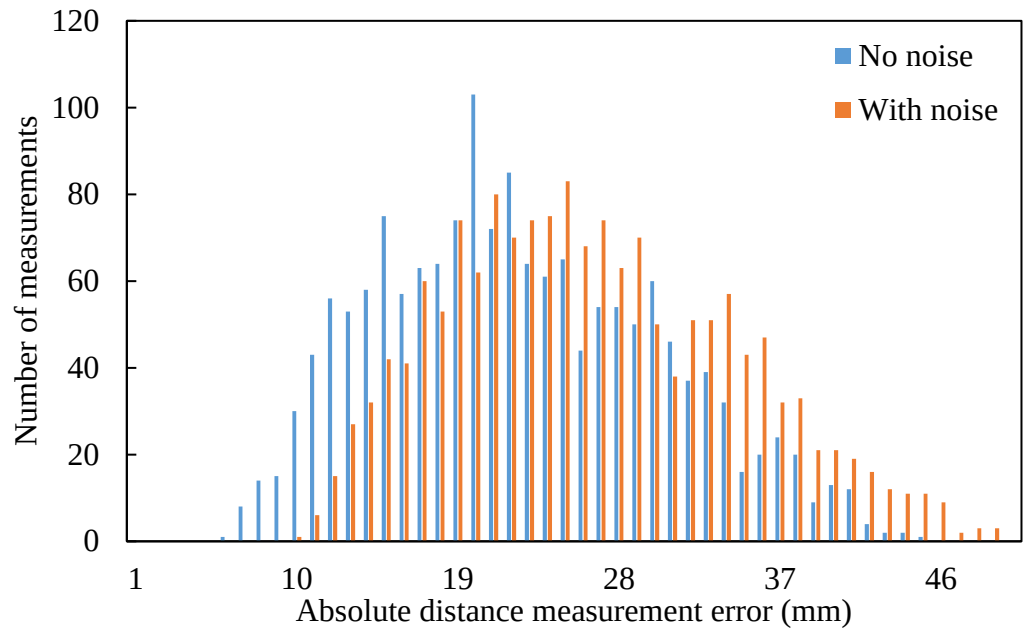
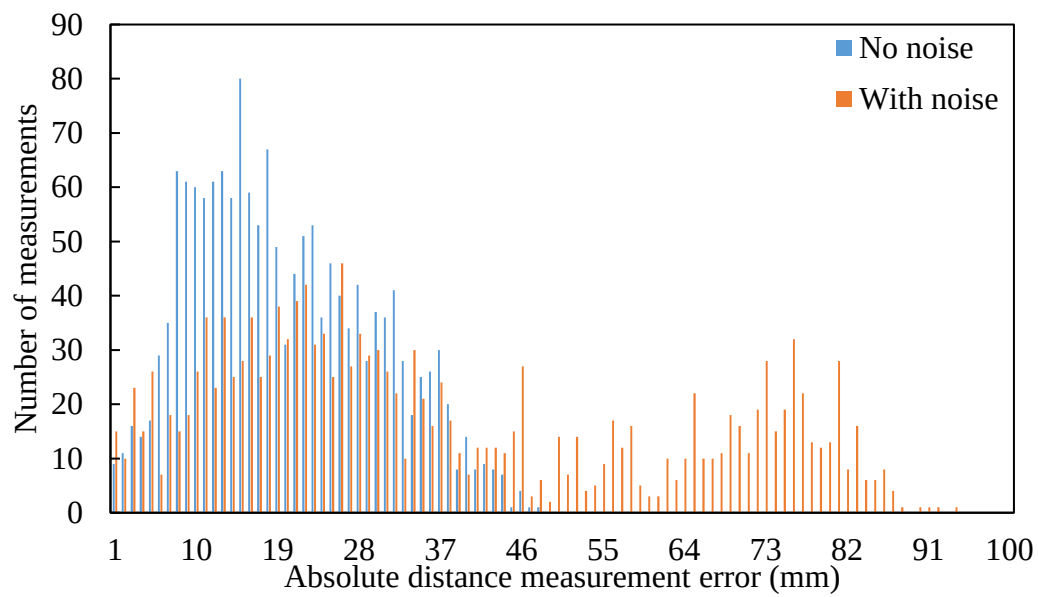


Fig.4.9. Correlation of the TDMA (a,b) and FDMA (c,d) signals with the non-operating quadcopter (a,c) and operating quadcopter (b,d)



(a)



(b)

Fig.4.10. Histogram of the absolute distance measurement error of TDMA (a) and FDMA (b) signals

Fig.4.10 shows the histogram of the absolute distance measurement error of

TDMA (Fig.4.10(a)) and FDMA (Fig.4.10(b)) signals without the quadcopter noise (blue legend) and with the quadcopter noise (orange legend). The mean absolute error of distance measurement of the TDMA modulation without and with quadcopter noise, was 22.5 mm and 26.4 mm, respectively. With the quadcopter noise, the mean absolute distance error using FDMA signals increased from 19.8 mm to 37.2 mm because of the wrong peak detection. Compared with the TDMA signals, the FDMA signals have larger distance measurement error when the quadcopter noise exists. So, the TDMA signal has better accuracy of positioning and distance measurement with the quadcopter noise, due to smaller peak detection error than in FDMA signals.

The sound pressure level of the TDMA and FDMA channels using three propeller models are shown in Fig.4.11. The sound pressure level of the noise in TDMA 12 kHz to 36 kHz is around 72 dB. The sound pressure level of the four channels in FDMA are 73, 64, 64, and 59 dB, which decreased because the noise spectrum in high frequencies decreased gradually (Fig.4.4).

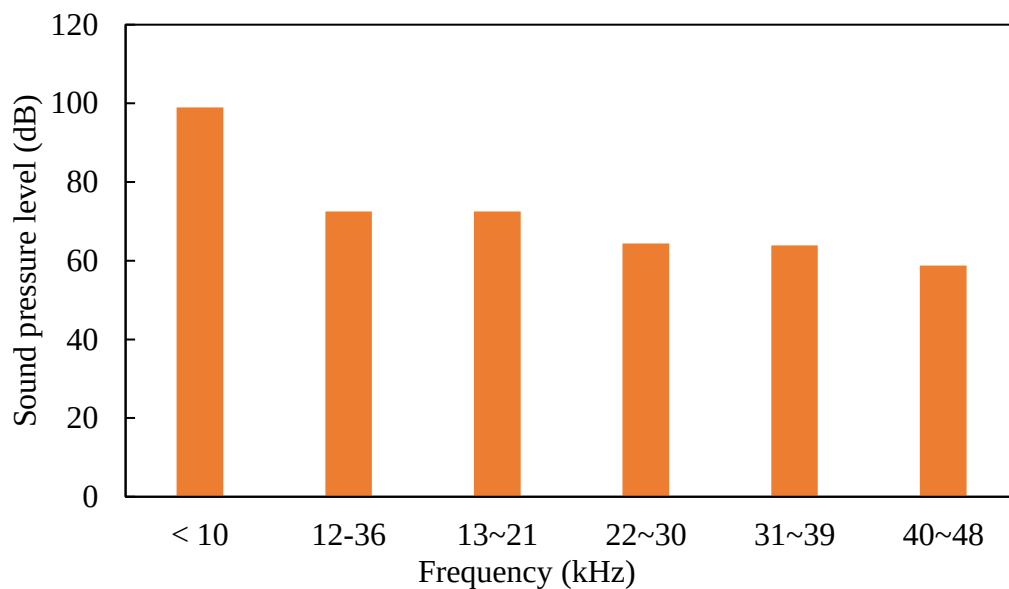


Fig.4.11. The sound pressure level of the TDMA and FDMA channels

Fig.4.12 shows that the SNR_{corr} value of the TDMA signal and four channels of the FDMA signal decreased with the distance from the acoustic noise by the quadcopter. The four channels of FDMA were labeled as FDMA1 to FDMA4. The TDMA and FDMA have the same decreasing trend with distance, because the noise at the microphone is relatively constant and the sound pressure level of the SSSound at the microphone is decreased. The frequency in channel 4 of the FDMA is 40 kHz to 48 kHz. The sound pressure level attenuation in high frequencies were stronger than low frequencies (Bass et al., 1995; Buckingham, 1997), so the noise tolerance of channel 4 of FDMA decreased faster than other channels. The distances from FDMA channel 4 that were larger than 14 m were difficult to detect. While the SNR_{corr} value of the TDMA signal at 14327.1 mm is 17.1, the TDMA signal can be used for a longer distance measurement. For the FDMA signals, due to the sound pressure level damping in high frequencies, the measurement distance is limited in 15 m when the thrust of the quadcopter reaches 9.75 N. Considering the coverage distance, the TDMA based SSSLPS has a larger potential than the FDMA system to be used for quadcopters in greenhouses.

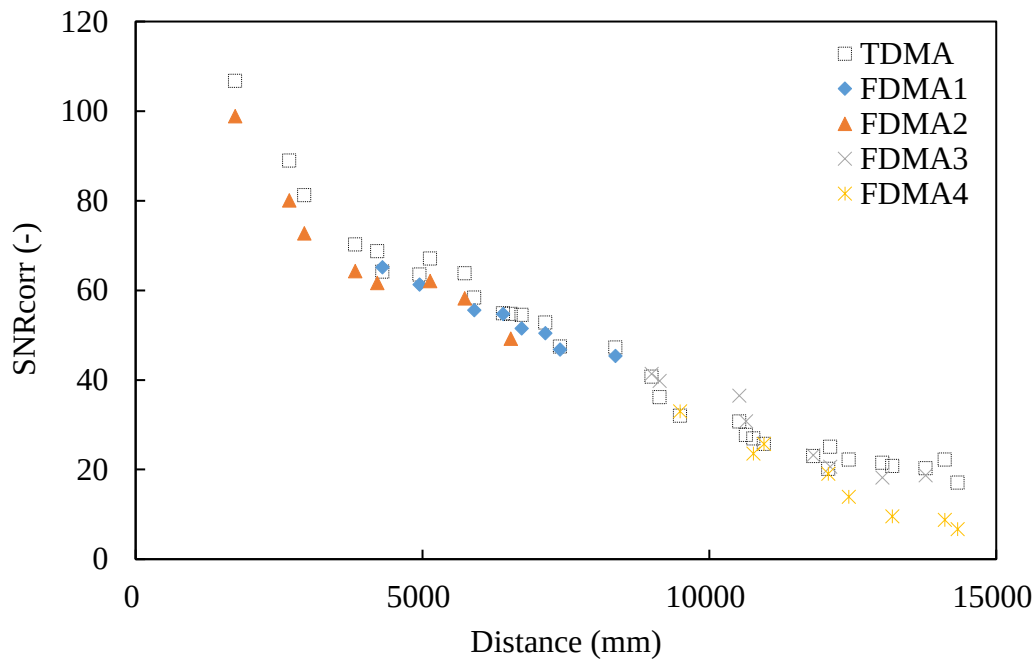


Fig.4.12. Signal strength decrease with distance

4.4 Conclusions

To evaluate the ability of the SSSLPS to be used as a positioning system on a quadcopter, the acoustic noise spectrum from the quadcopter and noise tolerance of the SSSLPS were analyzed. Then, the experiment in the greenhouse was conducted to evaluate the accuracy of SSSLPS on the quadcopter. The quadcopter noise in the SSSound range is mainly broadband aerodynamic noise. To improve the noise tolerance of SSSLPS, the SSSound signal can use longer M-sequence lengths and shorter chip rates. The longer M-sequence lengths can be used for the TDMA system. The shorter chip rates can be used for the FDMA system. The positioning error of the FDMA system is 31.6 mm, which is larger than the 23.2 mm positioning error of the TDMA system with quadcopter noise. This is because the FDMA signals with the small chip rate were affected by the carrier wave, and the correct peak is difficult to detect. Meanwhile, considering the sound pressure level damping in the high frequencies of the FDMA system, the TDMA is better used for the quadcopter, since it has larger measurement areas than the FDMA system.

The moving quadcopter, with the TDMA modulation system, has a larger positioning error during movement since the four speakers emit sound signals at different times and need high positioning update frequency. The Inertial navigation system uses the Inertial Measurement Unit (IMU) and can be used to estimate the position (Hellmers et al., 2018), but with accumulated error. One possible solution is sensor fusion with the IMU and SSSLPS, using Extended Kalman Filter (EKF) to minimize the positioning error. More work needs to be done to enlarge the coverage of this system. In this experiment, we measured the position in a 12×6 m area with four speakers. To enlarge the coverage area of SSSLPS, the typical method is to use more nodes (Atri Mandal, 2005; Kim and Choi, 2008) and more speakers in our system.

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Chapter 5 *Doppler shift compensation for positioning the moving robots using spread spectrum sound-based local positioning system*

5.1 Introduction

Various robots have been developed to aid vegetable and fruit production in greenhouses, but most are slow moving and need to be large to carry all the vegetables or fruit. We proposed a new robotic system with multiple ground-based robots and a quadcopter in order to lower costs and overcome the issues. A SSSLPS is used to guide the path of these robots.

In order to localize these moving robots with a sound-based positioning system, it's necessary to compensate for Doppler Shifts in the sound signals. The filters can be used if the position can't be estimated with the doppler shift. The previous research using particle filter(Muller et al., 2006) tested a 40 kHz ultrasonic signal within $2.5 \times 1.4 \times 2$ m measurement area and reached around 25 cm error. Another research compared the Unscented Kalman Filter (UKF) and Newton-Method (Ko et al., 2008) using 40kHz ultrasonic signal area within $3 \times 3 \times 2.6$ m and reached 75.2 mm and 252.2 mm average positioning error of two filters. Previous research (Widodo, 2013) used an additional ultrasound signal, beside the SSSound signal, to estimate frequency shift. This methodology is limited by sound levels in the SSSound and sensitivity to sound reflection.

In this research, we proposed a new compensation method based on the idea to erase the M-sequence in the SSSound and only keep the carrier wave. By analyzing the frequency spectrum of carrier wave in the received signal, the frequency shift on carrier wave and chip rate is to be estimated.

5.2 Algorithm for doppler shift compensation

The block diagram of the proposed compensation algorithm is shown in Fig.5.1. Here a cosine carrier signal is used to illustrate the algorithm. The received signal $r(t)$ can be expressed as the following equation,

$$r(t) = A(t)M(t) \sin((\omega_0 + \Delta\omega)t) \quad (5.1)$$

where, $A(t)$ is the amplitude, (t) is the m-sequence, ω_0 is original frequency, t is the time (1/96 ms), and $\Delta\omega$ is the frequency shift.

The received signal passes through the band pass filter (BPF) to cut the noise over the SSSound range. A sine wave is multiplied to shift the received signal into low frequency range. Then a low pass filter (LPF, 8kHz) filters the sound signal over than 8kHz. The squared received signal can is,

$$r^2(t) = A^2(t)M^2(t) \sin^2((\omega_0 + \Delta\omega)t) \quad (5.2)$$

The $r^2(t)$ is used to evaluate the frequency shift $\Delta\omega$ by the following equations,

$$R_2(k) = FFT(r^2(t)) \quad (5.3)$$

$$\Delta\omega = \frac{\omega_d - 8000}{2} - \omega_0 \quad (5.4)$$

where, $R_2(t)$ is the frequency spectrum of $r^2(t)$ by FFT, ω_d is the peak around 8 kHz detected by $R_2(t)$.

Based on the estimated frequency shift $\Delta\omega$, the new reference signal s_{DSC} is created by the following equations. This new reference signal is used to calculate the cross-correlation with the received signal.

$$f_{cnew} = f_c + \Delta\omega \quad (5.5)$$

$$f_{chipnew} = f_{chip} + \Delta\omega$$

$$s_{DSC}(n) = \sin\left(\frac{2\pi n f_{cnew}}{f_s}\right) \times M(\text{floor}(\frac{f_{chipnew}}{f_s} \times n)) \quad (5.6)$$

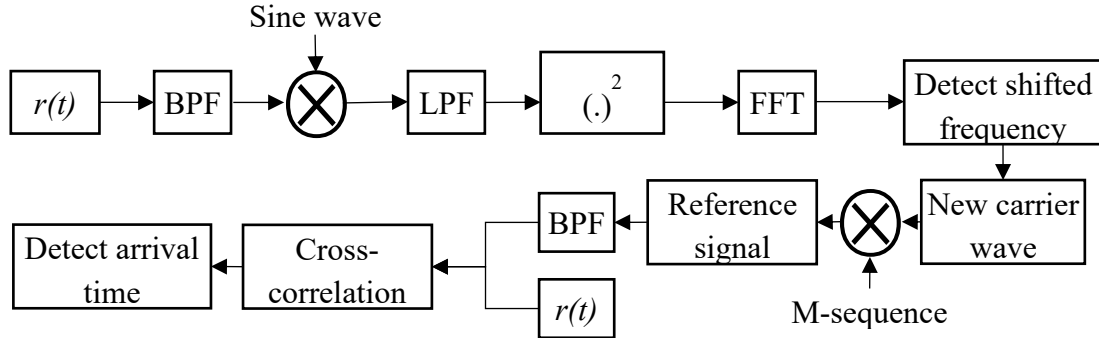


Fig.5.1 Block diagram for compensating the doppler shift

5.3 Materials and methods

The SSSound signal in this experiment was from 10 to 18 kHz. Its carrier wave was 14 kHz. The frequency of sine wave in compensating algorithm is 10 kHz. The experimental setup is shown in Fig.5.2 The microphone (SPM0404UD5, Knowles Electronics) was set on a conveyor. Then the microphone was conveyed towards the Tweeter (FT28D, FOSTEX) at various velocities. The length of the conveyor was 2 m, and the tested experimental velocities v_{mic} were around 0.1, 0.2, 0.3, 0.4 and 0.5 m/s. The SNRcorr of received signal emitted at around 400 mm to the tweeter was used to evaluate the performance of compensation algorithm.

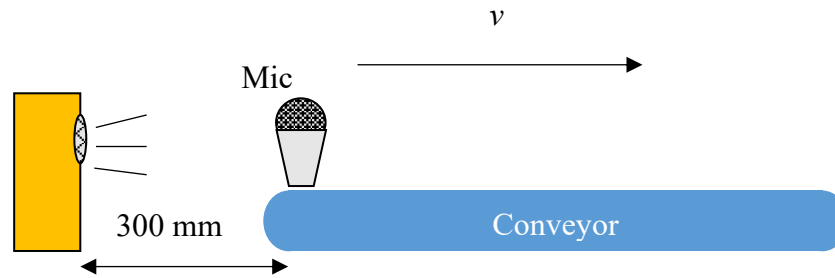


Fig.5.2 Experimental setup on conveyor

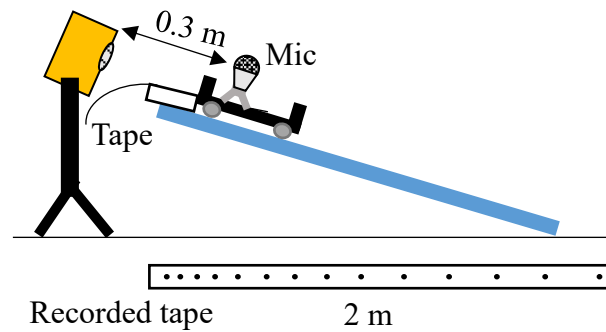


Fig.5.3 Experimental setup on testing bed

The acceleration was generated by changing the angle of inclination of the sloping testing bed. The acceleration was provided by the recorded tape from RBI timer (60 HzPH-100, Rakuten).

5.4 Results and discussion

Fig.5.4 shows the results of SNR correlation without (Non-compensation) and with (Compensated) the Doppler Shift compensation. Normally a sound signal can't be detected by cross correlation without Doppler Shift compensation for an object moving faster than 0.2 m/s. With the compensation algorithm, all sound signal, irrespective of velocity, can be detected with a stronger signal strength. The ground robot introduced

in the first chapter normally has a velocity lower than 0.3 m/s because this velocity is limited by the distance between plants and vehicle type.

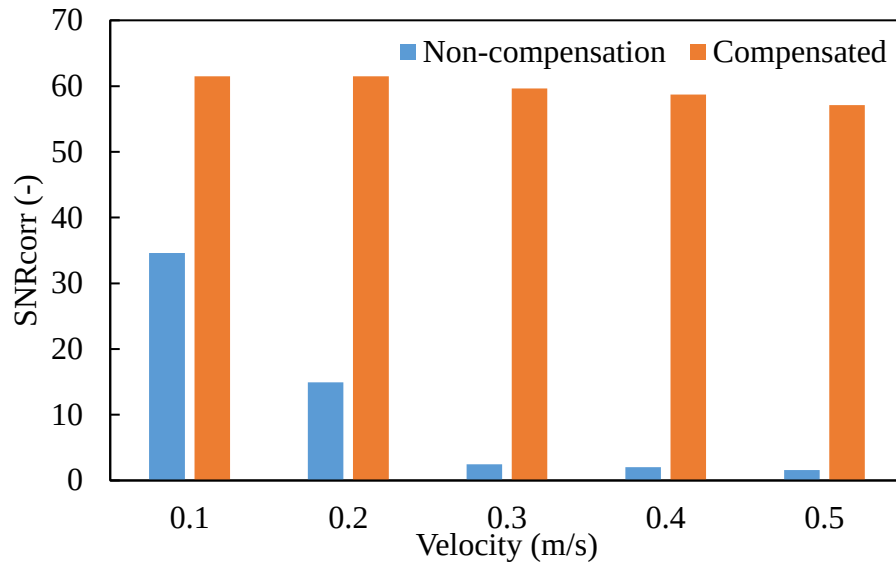


Fig.5.4 SNR correlation of signal

Fig.5.5 is the ranging result with Doppler Shift compensation at 0.5 m/s movement. A linear distance increase can be observed with moving velocity of around 502.5 mm/s.

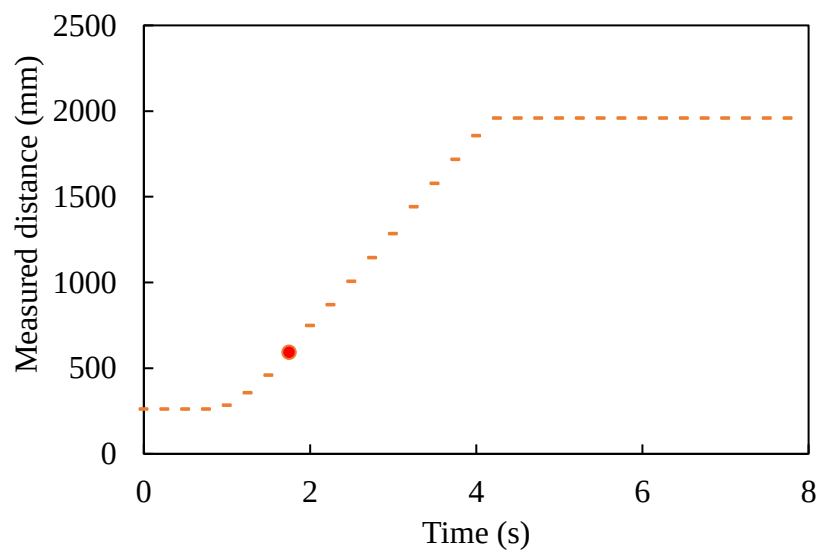


Fig.5.5 Distance measurement at 500 mm/s

The distance measurement in Fig.5.4 is used to illustrate the performance of the algorithm. In this experiment, the microphone is moving toward to the speaker, so the frequency shift can be calculated by the following equation,

$$f' = \frac{v + v_{mic}}{v} f \quad (5.5)$$

where, f is the original frequency, f' is the frequency with doppler shift and v is the sound velocity estimated by the temperature. In this measurement, the sound velocity is 339400 mm/s. The microphone is moving toward to the speaker, so the frequency shift is increasing. The frequency spectrum (FFT in Fig.5.1) of the distance measurement at 0.5 m/s is shown in Fig.5.6. This example (red point in Fig.5.5) is measured around 400 mm to the speaker with 12 Hz frequency shift at 8000 kHz estimated the frequency spectrum. Based on Eq.5.5 the moving velocity of microphone is 509.1 mm/s $(=(8012/8000) \times 339400 - 339400)$, which is similar to the 536.3 mm/s velocity calculated by the ranging result.

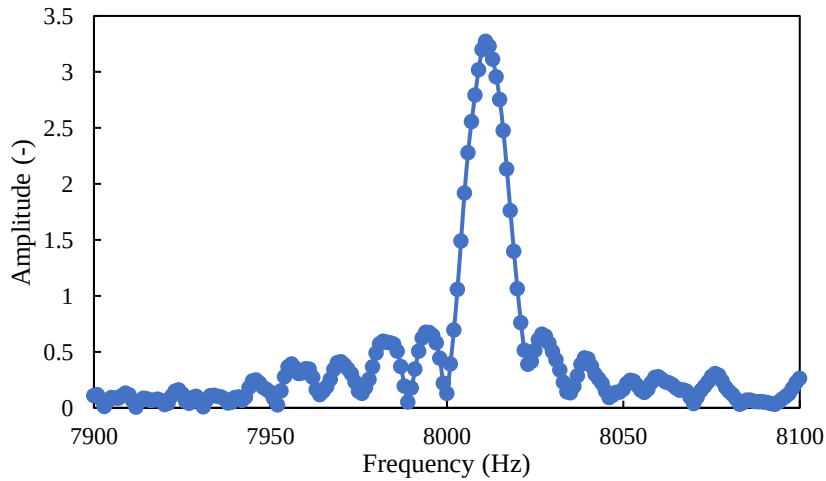


Fig.5.6 Frequency spectrum for estimating frequency shift (peak 8021 Hz)

The experimental result of moving ranging samples on the testing bed with accelerated velocity is shown in Fig.5.7. Without compensation the distance can't be

measured even with 0.06 m/s^2 acceleration. In contrast, all the distance can be measured in this experiment with high SNR correlation after the doppler shift compensation. With the increasing acceleration, the SNRcorr decreased because the reference signal and the received signal can't totally match.

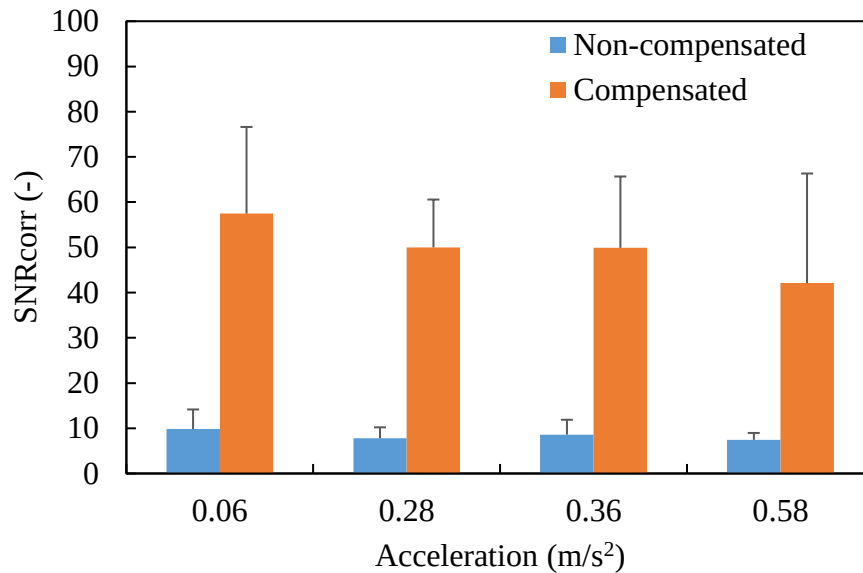


Fig.5.7 SNR correlation with accelerated velocity

5.5 Conclusion

To compensate the frequency shift for distance measurement, the compensating algorithm estimating frequency shift by the carrier wave in the received signal was developed. The experiment on the conveyor covers the possible moving velocity of the robots in a greenhouse. The results show the compensating algorithm can compensate the frequency shift and measured distance with moving microphone. In our experiment, it covers the 300 mm/s velocity and 300 mm/s^2 acceleration, which is the possible velocity of the ground robot in a greenhouse. In the future, the positioning accuracy with moving microphone needs to be evaluated. The difficulty of the future experiment is another positioning system with 100 Hz sampling rate and within 1 mm accuracy.

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Chapter 6 *Conclusions and future plan*

6.1 Conclusions

The small distributed robots with a quadcopter working in the greenhouse have the potential to be commercialized in the future since their low weight, less cost and higher efficiency. To guide the path of these robots, a positioning system is needed for the greenhouse environment. A lot of researcher focusing on the local positioning system in the GPS-denied environment. During these researches sound-based positioning system is an attractive one for the greenhouse. This research builds the passive SSSLPS for the crawler robots and the quadcopter in the greenhouse. The passive SSSLPS with TDMA and FDMA doesn't suffer from the noise interference between speakers, so the amount of positioning target is unlimited. The followings are the main findings in this work.

Chapter 2 introduces the structure of the passive SSSLPS using four speakers at the corner and microphones on the robot. Comparing with the active SSSLPS, the passive SSSLPS can localize multiple targets with light microphones on robots and doesn't have noise interference between speakers. The position can be estimated using at least three distance from speakers to microphone. In this research, we mainly use the wire linked system because the low time delay and easy to be compensated. The wireless system also was developed and can be used in the future experiment.

Chapter 3 proposed two methods using two microphones on the robot. Due to the passive structure put speakers near to the greenhouse wall, there has strong reflected wave. A new threshold is designed and can detect the direct wave from speaker to microphone. The experimental result shows the second method can reach 1.55° orientation accuracy whose accuracy meets the most requirements for the greenhouse

robots. The accuracy of this method is mainly influenced by the accuracy of peak detection that is affected by carrier wave, so is more suitable for the TDMA signals because of the shorter peak width than FDMA signals.

Chapter 4 evaluates the noise tolerance of SSSound against the quadcopter noise by experiment. The acoustic noise of a quadcopter in high frequency (larger than 10 kHz) is generalized as a wide band aerodynamic noise. It was found the SSSound can tolerate quadcopter noise with good SNR correlation and noise tolerance can be improved by changing properties of SSSound. The experiment in the greenhouse with an operating quadcopter achieved a positioning accuracy of 23.2 mm and 31.6 mm within 12×6 m for both TDMA and FDMA. The TDMA signal has better accuracy than FDMA signals because it has shorter peak width. But the limitation of TDMA signal is the large error during movement and needs to be solved in the future research.

Chapter 5 develops the compensating algorithm to localize the moving robot by SSSLPS to minimize the effect of frequency shift. New proposed method estimates the frequency shift by the carrier wave in the received signal. The experiment with constant velocity from 0.1 to 0.5 m/s and acceleration between 0.06 to 0.58 m/s² shows the compensating algorithm can increase the signal strength of SSSound, and the frequency can be estimated with clear shift on the frequency spectrum.

The passive SSSLPS that developed for the distributed ground robots in a greenhouse is necessary to have the function of orientation estimation to guide the direction of the robots. The SSSLPS is based on the distance measurement between speaker and microphone. So, the noise interference with a quadcopter and Doppler Shift at the received signals was evaluated and compensated for being able to measure the distance by SSSLPS. In conclusion, the SSSLPS is an accurate positioning system for the crawler robot and has the potential to be stable and low-cost platforms for the

quadcopter.

6.2 Future plan

In chapter 4, the TDMA and FDMA as the solution for the near-far problem (Agee, 1994) were compared. Here the TDMA and FDMA are compared in the following table. For positioning the moving robots, the FDMA is better because the emitting time of all signals is same, while the TDMA emitting four sound signals at different robot position that leads to bigger positioning error. The wrong peak detection will lead to big orientation error, so the FDMA signals are not suitable for orientation estimation.

Table 6.1 Comparison of TDMA and FDMA

	Advantages	Disadvantages
TDMA	● Longer signal with better noise tolerance. ● Easier to detect correct peak.	● Larger positioning error during movement.
FDMA	● Synchronized emitting time.	● Long signal length. ● Difficult to detect correct peak. ● Faster sound level damping in high frequency.

6.2.1 Correct arrival time detection

For the FDMA signals, the algorithm for detecting correct peak should be developed. From the literature, the coherent modulation (Zhai, 2018) and Non-coherent Delay Lock Tracking Loop (Non-coherent DLL) (Chun-Chieh Fan and Zsehong Tsai, 1999; El-Tarhuni, 2004; Vali et al., 2010) maybe possible solution.

Here the author evaluated the coherent modulation in the pre-experiment using TDMA signals. The algorithm of coherent demodulation is shown in Fig.6.1. After multiplying received signal and carrier wave, the output signal from the LPF only has

the phase. The results (Fig.6.2) show after the coherent modulation and the correlation only has one peak over threshold.

The algorithm described above should be evaluated their performance in the future research using the FDMA signals.

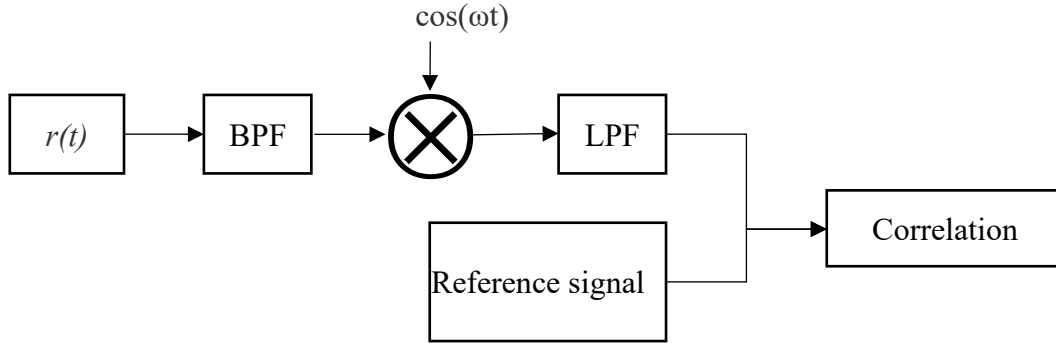


Fig.6.1 The algorithm of coherent demodulation

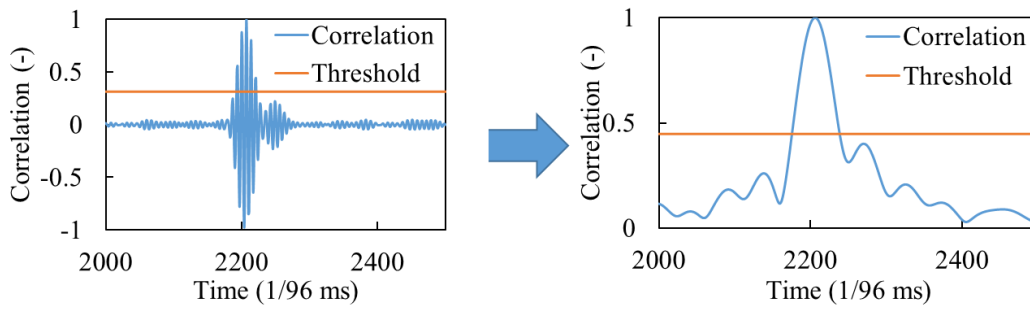


Fig.6.2 An example of the correlation

6.2.2 Sensor fusion with SSSLPS and IMU

If the TDMA signals are used, the possible solution for positioning moving robot is sensor fusion with SSSLPS and IMU. Meanwhile, to increase the positioning accuracy the RGBD camera can be added in this sensor fusion system.

The inertial navigation system (INS) and RGBD camera will be used for the multi-

sensor fusion. The INS can give 100 Hz acceleration data and RGBD can give the position and velocity data by optic flow (Mercado et al., 2013) with 60 Hz. The problem with INS and camera is that they accumulate error with the time that can't meet the requirement for an accurate positioning system in the greenhouse, while this accumulated error can be corrected using SSSLPS.

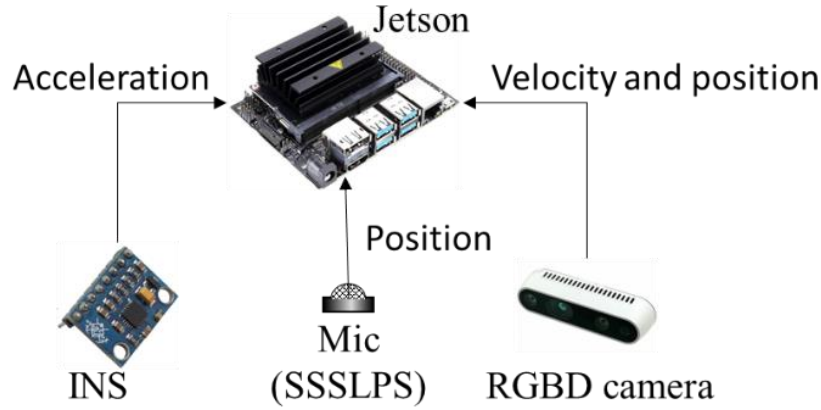


Fig.6.3 Setup for the multi-sensor fusion

The multi-sensor data fusion is realized by an extended Kalman Filter (EKF) (Yazdkhasti and Sasiadek, 2018) that the main equation is the following:

$$\hat{x}(k) = \hat{x}^-(k) + G(k) (z_i(k) - h(\hat{x}^-(k))) \quad (6.1)$$

where $\hat{x}(k)$ is estimated position, velocity and INS offset at time k , $G(k)$ is Kalman gain.

At time k , $z_i(k)$ is the measured distance determined by SSSLPS, if position has been measured by SSSLPS. If not, $\hat{x}(k)$ is the estimated position determined by INS and camera. The position after sensor fusion by the Kalan filter is shown in the Fig.6.4.

There have two merits of the proposed system with sensor fusion. The EKF can

minimize the positioning error caused by the time delay of processing and flight time of the sound signal that was evaluated in my previous simulation (Huang et al., 2017). Another advantage of this system is the ability to detect the environment by the RGBD sensor such as obstacle.

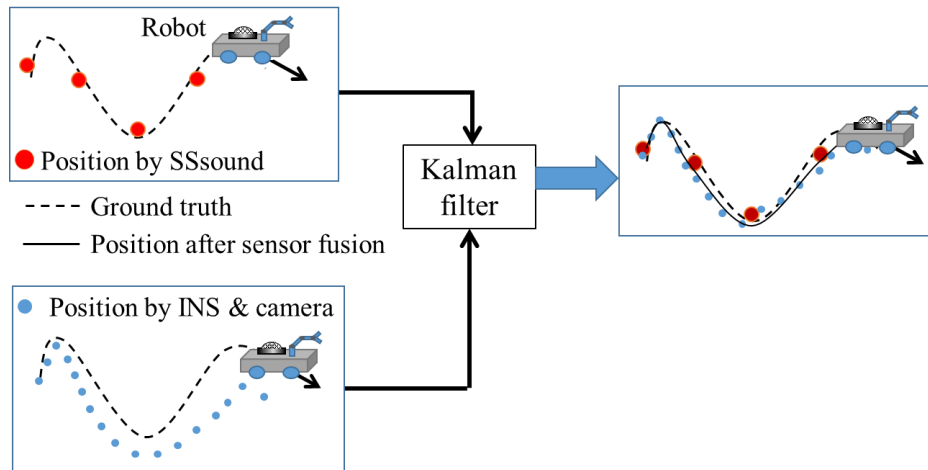


Fig.6.4 Estimated position by sensor fusion

After building the navigation system, we will conduct this experiment in the experimental farm of Kyoto University in Kizugawa City. The experiment will evaluate the performance of navigating the crawler robot in the greenhouse in 40 m x 9 m greenhouse with ridge-cultivated strawberry.

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List of Publication

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Conference:

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Measurement System using Spread Spectrum Sound. IFAC-PapersOnLine, 51(17), 108–111. (Oral presentation)

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