CHEMICAL ENGINEERING TRANSACTIONS
VOL. 58, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Remigio Berruto, Pietro Catania, Mariangela Vallone

ISBN 978-88-95608-52-5; **ISSN** 2283-9216
DOI: 10.3303/CET1758139

Is Spread Spectrum Sound a Robust Local Positioning System for a Quadcopter Operating in a Greenhouse?

Zichen Huang*[a], Masanori Ono[a], Tomoo Shiigi[b], Tetsuhito Suzuki[a], Harshana Habaragamuwa[a], Hiroaki Nakanishi[c], Naoshi Kondo[a]

[a]Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto, Japan
[b]Department of Ocean Mechanical Engineering，National Fisheries University, Shimonoseki, Yamaguchi, Japan
[c]Graduate School of Engineering, Kyoto University, Sakyo-ku, Kyoto, Japan
huang.zichen.22c@st.kyoto-u.ac.jp

This paper evaluates the robustness of a hybrid Spread Spectrum Sound Local Positioning System (SSSLPS)/ Inertial Navigation System (INS) navigation system for use with a quadcopter with respect to two issues: noise interference from the quadcopter (80 dB measured at 6cm over quadcopter), and positioning error caused by SSSLPS characteristics, such as distance measurement error, time delay and measuring interval. Results show the SSsound signal can be detected when the Signal Noise Ratio (SNR) was larger than -20.3 dB, and with an average two-dimensional (2D) positioning error less than 40 mm. These results indicate the hybrid SSSLPS/INS navigation system can be used to position a mobile quadcopter in a greenhouse.

1. Introduction

Automated robots are needed to reduce labor shortages and repetitive work. To date a number of robots have been developed for vegetable and fruit production in a greenhouse, such as strawberry harvesting robot (Hayashi et al.,2014), pesticide spraying robot (Liu et al.,2011), but many of these greenhouse robotic systems are slow, heavy and expensive; what is needed are low cost, mobile and robust platforms. A quadcopter, also called a quadrotor helicopter or quadrotor, is a kind of micro Unmanned Aerial Vehicle (UAV) propelled by four rotors (Hoffmann et al., 2004). They are a cheap, light and convenient platform that has been applied to precision agriculture in the field, such as spatial referencing, crop and soil monitoring, decision support and differential action (Abdullahi et al., 2015). Moreover, a quadcopter can work at any time according to the desire of the famer (Chris et al., 2015).
Normally, a Global Navigation Satellite System (GNSS) guides the quadcopter in the field, as well as guiding combine robots in the field (Iida et al., 2013). But their high cost and low accuracy in indoor environments limits their application for quadcopter navigation in the greenhouse. A number of other methods have been researched for localization in greenhouse, such as rails (Hayashi et al., 2014), inductive sensors (Philip et al., 2005) and sound Spread spectrum Sound Local Positioning System (SSSLPS) (Widodo et al., 2013). Of these SSSLPS is an attractive potential positioning system for use in the greenhouse, given its high measurement accuracy and low cost. A SSSLPS has been built and used for estimation of distance measurement in a 30 m x 30 m area, the Root Mean Squared Error (RMSE) of average two-dimensional (2D) positioning accuracy of this system was 20 mm (Widodo et al., 2014). For localizing a quadcopter, strong noise interference from the quadcopter (80 dB measured at 60 mm over quadcopter) may affect the positioning system. The research has focused on developing agricultural robot applications with a low measurement frequency interval (3 Hz), which is not fast enough to control a quadcopter. We propose that a hybrid SSSLPS/INS navigation system with increased update frequency could be used to localize a mobile quadcopter in a greenhouse.
The final goal of our research is to realize a hybrid navigation system for quadcopter operation in a greenhouse. But two main problems need to be overcome: noise interference from the quadcopter, and positioning error caused by SSSLPS characteristics, such as distance measurement error, time delay and measuring interval. So the objective in this paper is to evaluate the robustness of SSSLPS/INS hybrid

Please cite this article as: Huang Z., Ono M., Shiigi T., Suzuki T., Habaragamuwa H., Nakanishi H., Kondo N., 2017, Is spread spectrum sound a robust local positioning system for a quadcopter operating in a greenhouse?, Chemical Engineering Transactions, 58, 829-834
DOI: 10.3303/CET1758139

navigation system by analysing noise interference and positioning error. In order to evaluate the noise interference, the SPL of SSsound was checked against the SPL of noise by simulation and experiment. Positioning error was simulated using reasonable input values of distance measurement error, time delay and measuring interval.

2. SSSLPS/INS hybrid navigation system

2.1 System configuration

There are two main location architectures: with either a speaker (Sp) or a microphone (Mic) set on the the quadcopter (Quad). The inverse GPS-like system (active mobile architecture) uses a speaker on the Quad to transmit signals to each of the microphones set around the boundary (Figure.1 (a)). For GPS-like system, several transmitters are placed at known positions and are used to transmit their location on a wireless channel (Figure.1 (b)) (Adam 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).

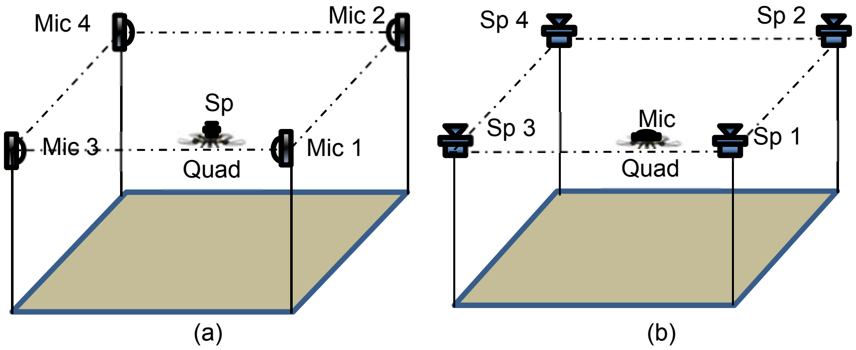


Figure.1 Configuration of inverse GPS-like (a) and GPS-like (b) system

2.2 Position estimation

Figure.2 illustrates the generation of the Spread Spectrum Sound (SSsound). The SSsound is generated by M-sequence, which is a kind of pseudo-noise sequence and has a good performance for autocorrelation. Next the carrier waves (24 kHz) are multiplied by the M-sequence to get the SSsound. The frequency of the SSsound signal ranges from 12 kHz to 36 kHz. Here Binary Phase Shift Keying (BPSK) modulation is used. The detailed properties of SSsound used in this work are summarized in Table.1.

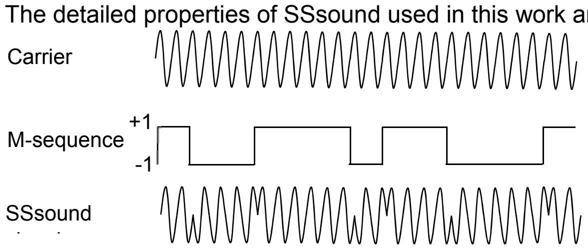


Figure.2 Generation of SSsound

Table.1 Property of Spread Spectrum sound

Property	Value/Remark
Sampling frequency	96 kHz
M-sequence length	1023
Modulation	BPSK
Carrier wave frequency	24 kHz
Chip rate	12 kcps

After the system generates the trigger signal, sound samples were recorded by microphones. Then the autocorrelation value based on the following equation was calculated:

$$C(t) = \sum_{n=0}^{N-1} s(n)r(n+t) \qquad (1)$$

where *n*=0, 1, 2 …N-1(N is the circle of SSsound).t is the time of received data, s is transmitted signal, r is received signal.

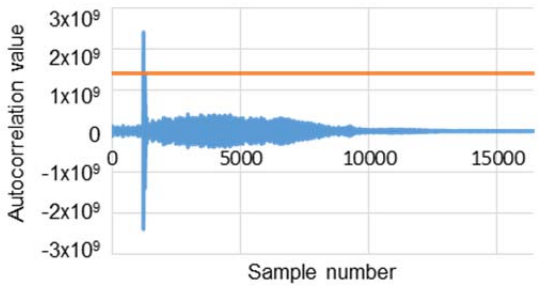


Figure.3 Auto-correlation value

Figure.3 shows an example of autocorrelation value with obvious peak. The peak represents the arrival time of the SSsound signal. The red line is the threshold value calculated by the following function, which is used to detect maximum value of autocorrelation (C_{max}).

$$c_{th} = \frac{C_{max} + C_{ave} + 3\sigma_{corr}}{2} \tag{2}$$

where C_{ave} and σ_{corr} is average value and standard deviation of autocorrelation.
Based on this, the distances from speaker and microphones can be calculated by multiplying time by sound velocity. Then these four known distances can be used to obtain a 3D position using trilateration.

2.2 Sensor fusion of SSSLPS and INS

SSSLPS works at 3 Hz, which is too slow to meet the requirement for a high position update frequency (100 Hz) when using a quadcopter. However, INS can work at over 100 Hz, and its acceleration sensor and gyro sensor can be used to calculate position, velocity and angle. The problem with INS is that it accumulates error, but this can be corrected using SSSLPS. To increase the update frequency, an extended Kalman Filter (EKF) was used in the following function to fuse the INS and SSSLPS:

$$\hat{x}(k) = \hat{x}^{-}(k) + G(k)\,(z_i(k) - h(\hat{x}^{-}(k))) \tag{3}$$

where $\hat{\boldsymbol{x}}(k)$ is estimated position, velocity and INS offset at time k , $\boldsymbol{G}(k)$ is Kalman gain.
At time k, $\boldsymbol{z_i(k)}$ is the measured distance determined by SSSLPS, if position has been measured by SSSLPS. If not, $\hat{\boldsymbol{x}}(k)$ is the estimated position determined by INS alone.

3. Devices and methods

3.1 Evaluation of noise interference

To investigate noise interference from the quadcopter, simulations were run to obtain the weakest SPL of SSsound which could be distinguished from the quadcopter noise level.The quadcopter is characterized by a high frequency (>6000 Hz) aerodynamical noise (Nanyaporn et al., 2016). In this research the noise of the quadcopter is assumed to be white Gaussian noise with the same frequency as the SSsound (12 kHz to 36 kHz). Here the period of the M-sequence used is 1023, which is same as our previous research with good noise tolerance. The noise was generated by white Gaussian noise with a constant amplitude. Then the SSsound signal was added into the generated noise. This was then used for the autocorrelation calculation (Eq.1). Then the amplitude of SSsound was changed to find out when there is no noise interference. The simulation was run 100 times to find the weakest detected SSsound by correlation Sound Noise Ratio ($CorreSNR$) based on the following principles:

$$CorreSNR = \frac{C_{max}}{C_{ave} + 3\sigma_{corr}} \tag{4}$$

$$SNR_{aver} - 3\sigma \geq 1 \tag{5}$$

where SNR_{aver} is average of $CorreSNR$, $\boldsymbol{\sigma}$ is standard deviation of $CorreSNR$.
We then run experiments using quadcopter (X8W, Syma Model Aircraft) noise to check the validity of these simulations. A microphone (M30, Earthworks) was used to record the sound. The frequency response of this microphone is stable from 10 to 30 kHz (±3 dB).The noise meter (LA-4440, Ono Sokki) used works from 20 Hz to 12.5 kHz. While the spread spectrum of SSsound becomes a wider band from 12 to 36 kHz. So the microphone was set to record the sound from 0 to 48 kHz. The sound level of the quadcopter was used to

calculate the corresponding sound level at the same frequency range as the SSsound. The quadcopter noise was measured from 6 cm to 200 cm from the quadcopter for different SPL of noise. Six replicate measurements were made at each noise level. These results were then used to evaluate the validity of the simulated results using Root Mean Square Error (RMSE).

3.2 Simulations of positioning error

Assuming an architecture with four nodes positions at p_{m1}=(0, 0, 3000) , p_{m2}=(40000, 0, 3000) , p_{m3}=(0, 40000, 3000) , p_{m4}=(40000, 40000, 3000), a quadcopter was flown in a horizontal circular path three times with a constant radius of 10000 mm and velocity of 3 m/s. The center of the circle was at (20000, 20000, 2000).To increase the validity of these simulations, an acceleration sensor were selected to set the parameters (Table 1) in EKF.

Table.2 Acceleration properties

Property	Value/Remark
Type	MPU-6050，InvenSense.Inc
Measuring interval	0.01 s
Noise	Horizontal: 500 $\pm$50 mm/s^2 Vertical: 800 $\pm$ 50 mm/s^2

Three simulations (Table 2) of the positioning error generated by a hybrid SSSLPS/INS navigation system were run to estimate positioning errors using estimated values for input errors (distance measurement error, time delay and measuring interval) from previous research. As a result, positioning error at each input error was compared to find the effect of these parameters on the accuracy of the hybrid SSLPS/INS system.

Table.3 Simulations of positioning error

	Distance error(mm)	Time delay (s)	Measuring interval(s)
Simulation(1)	0, 25, 50,75, 100	0.5	0.25
Simulation(2)	30	0, 0.25, 0.5,0.75, 1	0.01
Simulation(3)	30	0	0.01, 0.25, 0.5,0.75, 1

4. Results and discussions

4.1 Evaluation of noise interference

The noise interference simulations indicate that the correlation peak can be detected when the SNR is larger than -20.3 dB (Blue line in Figure.4). Red points in Figure.4 are minimal SPL of SSsound which can be detected from quadcopter noise. The RMSE for both the simulated and experimental runs was 2 dB, thereby validating the simulation results. Normally if the quadcopter is treated as a point noise source, its noise in the SSsound range is larger than 60 dB. To navigate in 40 m x 40 m x 3 m space, a GPS-like system would need a higher SPL for the speaker, which wastes energy, is hard to realize, and is harmful to human ears. So this simulation confirms the best performance, in terms of minimal noise interference, is obtained when the quadcopter acted as a transmitter of the SS signal (speaker), with four microphones set at the corners acting as receivers.

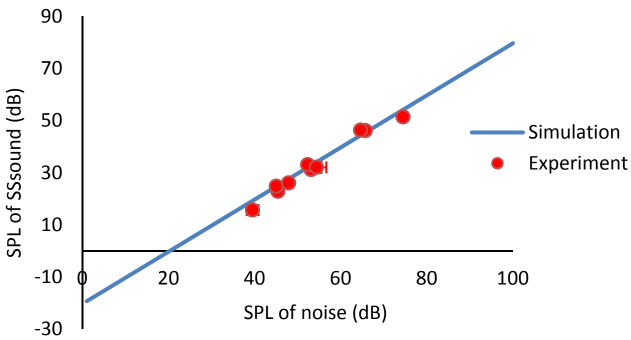
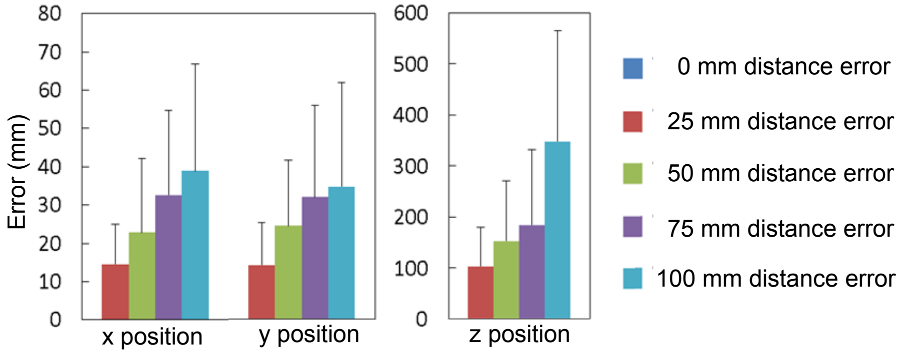


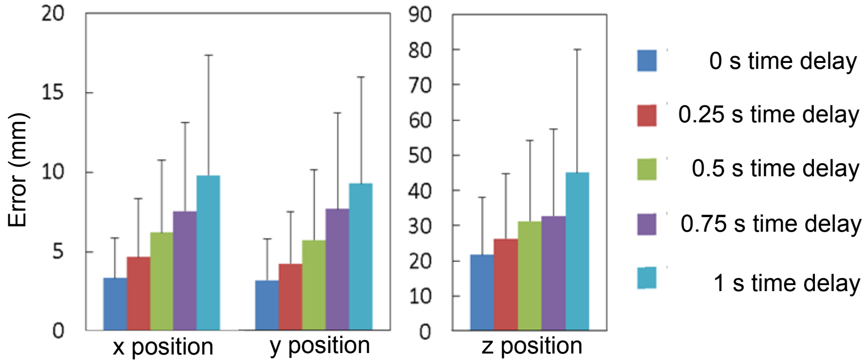
Figure.4 Minimal SPL of detected SSsound against noise

4.2 Simulation of positioning error

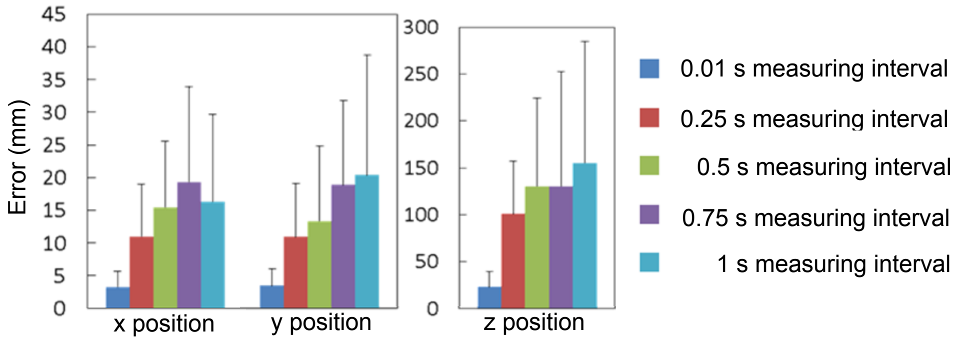
Figure.5 shows the simulation results of three-dimensional (3D) positioning error of x, y and x coordinate. The positioning error simulations confirmed that even when there are large input errors, the position still can be detected. With an increase in input values, positioning error increases, but the average positioning error is 40 mm, with little scattering of the error. The horizontal positioning errors caused by time delay and measuring interval were smaller than 50mm. By comparing the horizontal positioning error caused by the input values, it can be seen that the distance error has the largest effect. To increase the accuracy of the SSSLPS/INS system, distance error should be first considered.



(a)



(b)



(c)

Figure.5 Positioning error caused by distance measurement error (a), time delay (b) and measuring interval (c)

The vertical error was 5 to 7 times larger than horizontal positioning error due to poor arrangement of the microphones relative to the transmitter (speaker). Figure.6 illustrate this phenomenon. The circle is the measured distance by SSsound. Dilution of Precision (DOP) was used to evaluate the multiplicative effect (Richard 1999). The average horizontal DOP is 1.00, which is an ideal value indicating horizontal position accuracy can be achieved at all times. The black area shows the positioning area. The vertical DOP is 8.86; a high vertical positioning error. To increase the vertical positioning accuracy, another sensor is needed in future research.

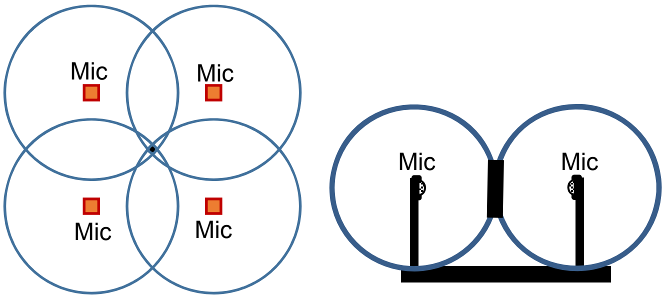


Figure.6 Horizontal (a) and vertical (b) positioning error

5. Conclusions

In order to evaluate the possibility of using a hybrid SSSLPS/INS system for quadcopter navigation, noise interference from the quadcopter, and positioning error of the SSSLPS/INS system were analyzed. Using a noise simulation, which assumes a noise interference from the quadcopter similar to SSsound, the SSsound peak could be detected when the SNR was larger than -20.3 dB. These simulated results were then experimentally validated. The inverse GPS-like system, which was minimally influenced by quadcopter noise, was confirmed to give the best performance. The simulations indicate mean horizontal positioning error is 40mm, but the vertical error is 5 to 7 times larger. In conclusion, quadcopters with a hybrid SSSLPS/INS navigation system, by meeting 2D positioning accuracy requirements for most greenhouse applications, have the potential to be robust and low cost platforms for automated greenhouse operations in the future.

Reference

Abdullahi H.S., Mahieddine F., Sheriff R.E., 2015, Wireless and Satellite Systems, Springer International Publishing, 388-400.

Adam S., Hari B., Michel G., Nissanka B.P., 2004. Tracking moving devices with the Cricket location system. The Second International Conference on Mobile Systems, Applications and Services.

Chris A., 2015, Cheap Quadcopters Give Farmers a New Way to Improve Crop Yields | MIT Technology Review, www.technologyreview.com/featuredstory/526491/agricultural-quadcopters/.

Hayashi S., Yamamoto S., Saito S.,Ochiai Y., Kamata J., Kurita M., Yamamoto K., 2014, Field operation of a movable strawberry-harvesting robot using a travel platform, Japan Agricultural Research Quarterly, vol.3 , 307-316.

Hoffmann, G.M., Rajnarayan, D.G., Waslander, S.L., Dostal, D., Jang, J.S.; Tomlin, C.J., 2004,The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control, 23rd Digital Avionics System Conference.

Iida M., Uchida R., Zhu H., Suguri M., Kurita H., Masuda R., 2013, Path-Following Control of a Head-Feeding Combine Robot, Engineering in Agriculture, Environment and Food, vol.2, 61-67.

Liu T., Zhang B., Jia J., 2011, Electromagnetic navigation system design of the green house spraying robot, IEEE.

Nanyaporn I., William N.A., William J.D., Sheryl M.G., Amanda D., 2016, Experimental Study of Quadcopter Acoustics and Performance at Static Thrust Conditions, 22nd AIAA/CEAS Aeroacoustics Conference.

Philip J.S., Tomonari F., Andrew B., 2005, Autonomous pesticide spraying robot for use in a greenhouse,. Proceedings of the Australasian Conference on Robotics & Automation.

Richard B. L., 1999, Dilution of Precision, GPS World, 52-59.

Widodo S., Shiigi T., Than N.M., Kikichi H.,Yanagida K., Nakatsuchi Y., Ogawa Y., Kondo N.,2014, Wind compensation for an open field spread spectrum sound-based positioning system using a base station configuration, Engineering in Agriculture, Environment and Food, 127-132

Widodo S., Wind and Doppler Shift Compensation for Spread Spectrum Sound-based Positioning System, 2013, PhD thesis, Kyoto University.