Static and dynamic evaluations of acoustic positioning system using TDMA and FDMA for robots operating in a greenhouse

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Abstract: Acoustic positioning system has great potential to be applied in a greenhouse due to its centimeter-level accuracy, low cost, and ability of extensive greenhouse coverage. Spread Spectrum Sound-based local positioning system (SSSLPS) was proposed to be a navigation tool for multiple agricultural robots by the authors' research team. However, to increase the system capacity for positioning multiple robots in a greenhouse, the near-far problem caused by the interference between speakers needs to be overcome. The use of different access methods, Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA), is essential in the SSSLPS system for solving the near-far problem. The static positioning in a greenhouse was first evaluated by setting different parameters to determine the optimal signal setting for a dynamic experiment. From that, the moving robot tests were added with a motion capture system and tested the performance of TDMA and FDMA. The results demonstrated that TDMA can be used in a stationary sound-based positioning system with 12.2 mm accuracy, but it has a time delay problem in dynamic positioning. A simulation was designed to mimic the position error increases with different moving speeds. Although FDMA has the sound damping problem in high-frequency regions creating a peak detection issue, it achieved a higher accuracy with an average position error of 62.1 mm compared to 180.3 mm of TDMA. This study shows that the TDMA method is suitable for static measurements, while the FDMA method is suitable for measuring dynamic objects and controlling mobile robots.

Keywords: greenhouse robots, positioning system, near-far problem, TDMA, FDMA
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1 Introduction

Robot technology has been advanced to such a degree that not only are they being widely used in industries, but also now being deployed in agricultural fields. Much of these early developments in agriculture have focused on large-scale, open-field robots operating in maize, rice[1], wheat fields[2], etc. Robot automation for closed greenhouses on the other hand has received much less attention. Those robotic systems that have been trialed in a greenhouse, apply several small ground robots to collaborate with multiple robots such as the crawler type[3] of ground robots that were proposed to fit the development of agricultural robots and achieve precision agriculture in greenhouses.

The most popular positioning system for agricultural robots is based on Global Positioning System (GPS)[4]. Unfortunately, a greenhouse is a GPS-denied environment due to signal dumpling and multipath effect. Another commercialized approach is using UWB for positioning a robot[5] with 10 cm accuracy. In a GPS-denied environment, an acoustic positioning system has the advantages of centimeter-level accuracy and low cost. However, many researchers did not consider the capacity limitation of their proposed systems[6,7], which means their systems were difficult to localize multiple robots. In order to localize the multiple robots in a greenhouse, the passive structure with the microphone mounted on the robot and four fixed speakers are necessary[8].

The research team of the authors of this study focuses on a spread spectrum sound-based (SSSound) local positioning system (SSSLPS) with centimeter-level accuracy. Although the modulated signals have a high tolerance to noise[9], the receiver is still hard to detect the weakened signals if the signal is far away from the source because when the signals from a nearer source stay strong, there is a channel interference between the speakers which is also referred to the 'near-far problem'[10]. Conventional research used different codes to classify acoustic signals using Code-division multiple access (CDMA) method[11], but it was not suitable for a greenhouse application due to the system settings. For example, in Figure 1, when the Receiver wants to receive a clear signal from Emitter 1, the signal from Emitter 2 becomes the

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noise source. In a greenhouse application, the distance between Emitter 2 and Receiver can be 1 m, and the distance between Emitter 1 and the Receiver can be much larger. For tackling the near-far problem, multiple access methods in signal processing communication were studied and there are two main methods, the Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA), suitable for SSSound signals as the former one uses the frequency bandwidth to separate the channel interference and the latter one separates the sound in the time domain. FDMA has the advantage of getting a fast synchronized measurement since many signals can be transmitted in different frequencies at the same time while the advantages of TDMA are having a longer signal for better noise tolerance and easier to detect the correct peak. However, the disadvantages of FDMA are the sound level damping in high-frequency areas, and also it is difficult to detect the correct peak[9]. TDMA has a limitation in time delay which is an obvious drawback, as the signals take time to be transmitted and they need to wait before the next sound wave is emitted. However, the time delay issue is not a problem when measuring static location but it might create a problem if TDMA needs to detect a moving target.

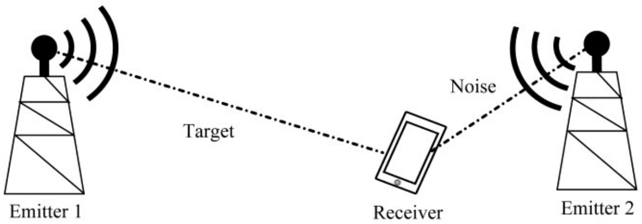


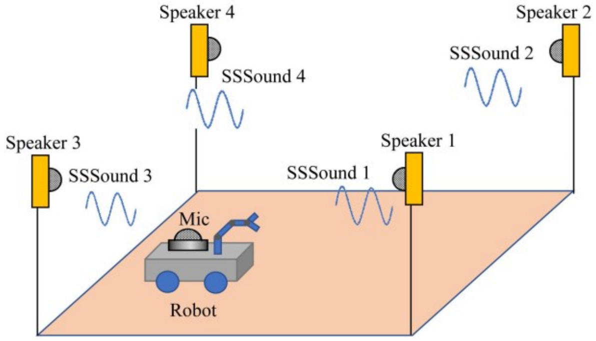
Figure 1 Near-far problem of distance measurement

In this research, two channel access methods were investigated, FDMA and TDMA to be applied to the SSSLPS system for positioning a target in a greenhouse and solving the near-far problem. An experiment was carried on in an actual commercialized greenhouse for static measurement, and then the dynamic measurement was also conducted using the motion capture system in a laboratory. The signal properties, system performances as well as effectiveness against the near-far problem with those two methods would be evaluated and discussed.

2 Material and methods

2.1 System architecture

The basic structure of passive SSSLPS (Figure 2) is to mimic a GPS-like system in that speakers like satellites were arranged at known positions and transmit the coded signals (SSSound), while the microphone was implemented on the robot as the target location, whose position was unknown.



Note: SSSound: Spread spectrum sound-based; SSSLPS: Spread spectrum sound-based local positioning system.

Figure 2 Setup of SSSLPS for a passive structure

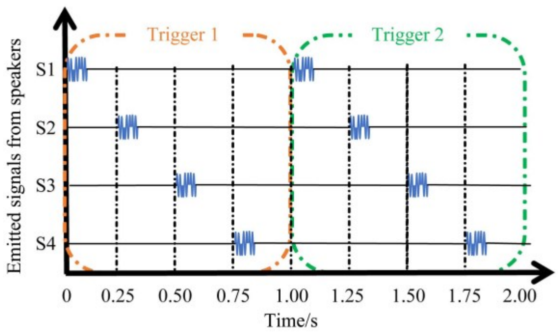
The emitted sound signal was modulated by M-sequence and a carrier wave. The sound signal will be received by the microphone, and as long as the trigger signal is detected, the cross-correlation $c(t)$ will be calculated immediately using Equation (1). Then the distance from a speaker to the microphone can be estimated using the measured time of flight (ToF) and sound velocity[12]. Finally, the position can be calculated by trilateration using three validated distances.

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

where, $s(n)$ is the original emitted signal; $r(n)$ is the received signal; n is the length of SSSound; t is the received time of the received data; N is the length of recorded signals.

2.2 TDMA and FDMA methods

Using the TDMA method, the speakers will insert a time interval to avoid transmitting in the same time slot. To make sure that signals arrive at different time slots, the time interval should be adjusted according to the operation area. The frequency of transmitting signals which means the measurement in 1 s, is set at 4 Hz. The scheme of emitting the TDMA sound signal is shown in Figure 3.



Note: S1: SSSound1; S2: SSSound2; S3: SSSound3; S4: SSSound4.

Figure 3 Emitted TDMA signals of four speakers

The signal properties were set the same, but every signal is emitted at different times. The time length of each TDMA signal package is 1.00 s. Thus, the time interval between every effective signal would be 0.25 s. Each time interval passed, a new range will be updated. The position will use the updated distance and the previous three updated ranges from different speakers to calculate the coordinates of the robot. For example, at 1.25 s in Figure 3, besides the distance data provided by S1 from trigger 2, the distance data from S2, S3, and S4 from trigger 1 are used for the position calculation.

When the target is in a dynamic state such that moving towards a direction, TDMA will encounter a time delay problem for the moving distance since there is a delay time from the separated time slots and resulting in an area of the possible target position.

For the FDMA method, the signals' frequency spectrum will be rearranged. As Figure 4 shows, the signal frequencies of speakers are arranged in separate regions of the frequency spectrum. This method divides the bandwidth into four and allocates them to different speakers. Conventionally, the bandwidth is divided into non-overlapping frequency sub-channels. To split the wide bandwidth of signal frequency of the original signal, which will lose the advantage of broad signal properties, such as graceful degradation and less bandwidth expansion[13]. With a small SSSound signal bandwidth, peak detection problems will occur as a disadvantage. Therefore, different signal overlap rates were tried to show the channel interference at different signal bandwidths.

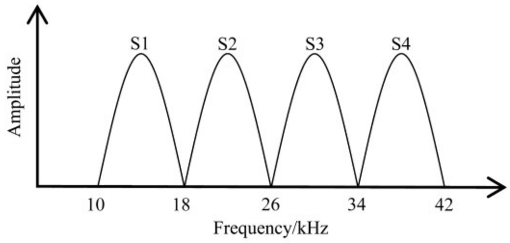


Figure 4 FDMA signal frequency spectrum

Four different signals were prepared to conduct the experiment as Table 1 shows, where f_c and F_{chip} are carrier frequency and chip rate, respectively. The first two signals TDMA and FDMA were used for comparing the two methods with each other, including the signal strength SNRcorr, ranging, and positioning accuracy. The last three signals, FDMA-I, FDMA-II, FDMA-III, are aiming to compare the FDMA signals. The percentage listed in Table 1 means the overlap rate of the frequency bandwidth of each signal to one of its adjacent signals. The minimum frequency of these signals is set to 10 kHz, which ensures that the system is not affected by the noise of agricultural machinery[14] and does not produce intense noise for people. Furthermore, according to the Canadian federal noise regulations[15], there is only a permissible exposure time of over 85 dB. So, if the human works 0.5 m away from the speaker, there is no limitation of exposure.

Table 1 Properties of SSSound signals

Signals	f_c/kHz	F_{chip}/kcps	M-sequence length
TDMA	24	12	1023
FDMA-I (0%)	14, 22, 30, 38	4	511
FDMA-II (25%)	14, 20, 26, 32	4	511
FDMA-III (50%)	14, 18, 22, 26	4	511

Note: SSSound: Spread spectrum sound-based; TDMA: Time Division Multiple Access; FDMA: Frequency Division Multiple Access. fc and F_{chip} are carrier frequency and chip rate, respectively. The same as below.

A method will be used to evaluate the noise tolerance of which the SSSound measurement is stable or unstable against the noise. The parameter is called correlation SNR (SNRcorr):

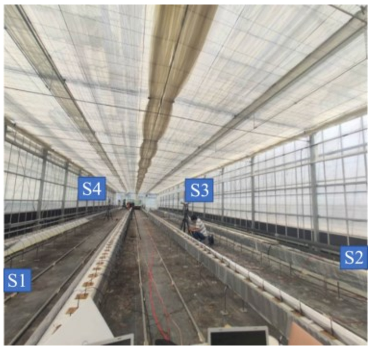
$$\mathrm{SNRcorr} = \frac{C_{\mathrm{peak}}}{C_{\mathrm{noise}}} \tag{2}$$

where, C_{peak} is the correlation value of the detected peak; C_{noise} is the average absolute value of the correlation before the detected peak. The parameter SNRcorr calculates the correlation of signal to noise ratio, therefore it can show an estimation of the signal's cross-correlation ability against noises.

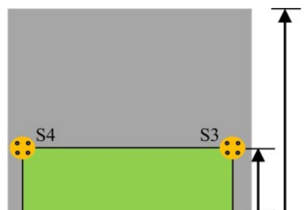
2.3 Static experiment

The sound signal will be generated by the PC and processed by an audio interface (OCTA-CAPTURE UA-1010, Roland, Japan). The audio interface will convert the digital signals to analog signals. The Amplifiers (Kama Bay Amp Rev. B, Scythe Inc., Japan) will amplify the signal. Then, the SSSound signal will be emitted by speakers (FT28D, Fostex Company, Japan), and received by a microphone (SPM0404UD5, Knowles Electronics, UK). To make sure the four speakers' output powers are the same, the measured sound signal was a uniformed Gaussian white noise. Then, the sound level is evaluated by a noise meter (LA-4440, Ono Sokki, Japan) at 90 dB (at a distance of 10 cm to the center of the speaker) using white noise. The thermometers (3670, Hioki, Japan) were set near the speakers and microphone to record temperature data. The ground true position data of speakers and microphone was acquired by a total station (SRX5XT 32T-11, Sokkia, Japan) with (1.5+0.0002%×measurement distance) mm accuracy[12].

The experimental area was set at 8.3 m×22.0 m rectangle area, which covered half of the total greenhouse area. The greenhouse from Figure 5a is table-cultured without any plants or obstacles in the target area, and tables are 1 m above the ground. The doors and windows were shut down to prevent ventilation. The speakers were set at 1.5 m above the ground at the four corners of the target area. One-quarter of the experiment area Figure 5b was measured, and the middle corridor was also included. The total station is set next to the field so that it can generate the reference coordinate for all the devices. The microphone stand, 1.3 m above ground, was placed at the points, and then began the measurement. To focus on the near-far problem, the obstacles on the sound path were avoided since they may lead to a multipath effect of sound signals. After the measurement (four signals by order (Table 1)) finished, the microphone stand was moved to the next point. The microphone was always set to face the direction of the side between speaker 1 and speaker 2 to ensure the worst situation of speaker 4 and speaker 3, which were most influenced by channel interference (near-far problem) in the experiment condition. At each measured position, the signals were measured one by one, and each signal was measured 20 times.



a. Kizu greenhouse



b. Experiment setup

Note: Blue dots in Figure 5b: measured positions of the microphone.

Figure 5 Insides of Kizu greenhouse and the experiment setup

2.4 Dynamic experiment

Besides the device used in the greenhouse experiment, for the dynamic experiment the wireless trigger signal which was emitted by the Zigbee device was used, the four speakers were set at (2.00±0.04) m height at four corners and the Doppler compensation algorithm[16] was also adopted in the distance calculation. Meanwhile, the motion capture system (Vicon Tracker, Vicon Industries Inc., USA), with 0.15 mm accuracy[17], was used with eight cameras at the edges for providing the reference position to evaluate the accuracy of SSSLPS during movement, as shown in Figure 6. For the dynamic settings, the experimental area was reduced to 7 m×5 m because of the limitation of the camera-based motion capture system that cameras were put at four corners, and in the middle of each edge SSSLPS receiver got the emit time of SSSound by measuring the received time of trigger 1. The other trigger signal was emitted and received by the audio interface. Then, motion capture coordinates were calibrated with SSSound coordinates provided by the total station. By using 18 points of position data, the coordinates were transformed at S1 to be the origin (0, 0), S1 to S2 as x-axis, and S1 to S3 as y-axis. The SSSound receiver was recognized as a motion capture model attaching 4 markers on it and was mounted on a crawler robot, which was controlled wirelessly and moved along the write arrow in Figure 6 at a low velocity of around 300 mm/s and the experiment repeated four times.

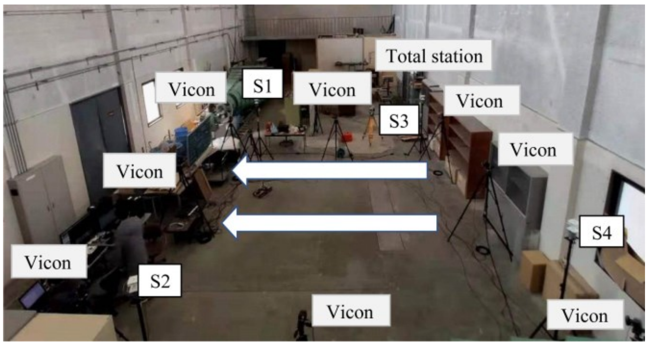


Figure 6 Experiment setup of dynamic measurement

Since the final goal is to operate the SSSLPS in an actual greenhouse, the experimental greenhouse setting was used for TDMA simulation at different moving speeds from 100 mm/s to 1000 mm/s. The robot was moving along the five tables with a range error of 25 mm and the simulation measurement was repeated 10 times.

3 Results and discussion

3.1 Static positioning of TDMA and FDMA

This research focused on 2D mean absolute positioning error so that the x and y coordinates differences would be evaluated. As introduced above, the error is calculated according to the reference ground truth measured by the total station. The detection rate was defined as the position error being less than 100 mm which is a similar accuracy to Ultra Wideband[5]. The detection rate was calculated for all the methods, the positioning error, and also the range error from the four speakers. During the whole experiment period, the indoor temperature was stable (24±0.6)°C which means that the sound velocity in the greenhouse is remain evenly distributed.

Table 2 Results of the twenty-one statics points in Kizu greenhouse

Signals	Detection rate/%	2D error/mm	Range error/mm
TDMA	100	12.2±8.1	12.6±7.7
FDMA-I (0%)	91	31.6±17.5	19.9±18.9
FDMA-II (25%)	71	52.0±45.4	34.8±52.3
FDMA-III (50%)	55	33.1±37.7	25.9±48.5

Table 2 shows TDMA has a detection rate of 100% and FDMA-I has a detection rate of 91%, while overlapped FDMA-II and FDMA-III only have 71% and 55% detection rates. It is clear to see that TDMA has the best results while FDMA-III (50% overlapped signals) has the worst detection rate. FDMA has worse overall performance than TDMA.

As Figure 7 shows the 2D positioning error distribution of the four methods, the result was separated by less than 20 mm, from 20 mm to 50 mm, from 50 mm to 100 mm, and larger than 100 mm. Besides the low detection rate of FDMA, the overlapping problem is one of the reasons that increased the range error and contribute to the high position error in FDMA-II and FDMA-III (25% as well as 50% of the overlapping frequency). TDMA is the best-performed method in this static greenhouse setting, FDMA-I without overlapping frequency is the best among all the FDMA performances.

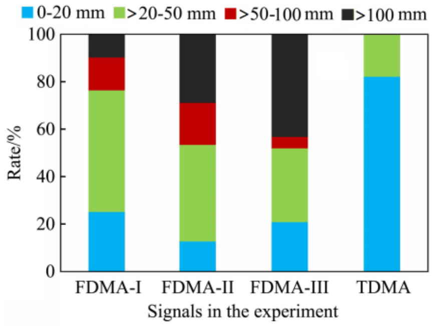


Figure 7 2D positioning error distribution

Figure 8 shows the correlation examples of FDMA-I and TDMA at position No.7, emitted from speaker 1. Both FDMA-I and TDMA should give the same time of arrival when the peak was located at the signal sample of 3561, as the signal transmission distance was the same. FDMA-I signal has a larger peak width than the TDMA's signal. The large peak width was determined by chip rate and carrier frequency. The large peak width will lead to a large tolerance for the true peak and reduce the accuracy of the distance calculation. Meanwhile, the threshold can identify the direct wave, which is the first received peak of the signal, from the reflected wave. As Figure 8 shows there was a clear peak in the TDMA received signal, the chip rate of the TDMA signal is 12 kcps, the M-sequence length is 1023, and the length of the sub-peaks is four samples, each sample represents 1/96 ms, which is resulted from the signal generation. This peak width will result in a maximum 14 mm error in distance measurement for TDMA[12] and a 52 mm error in FDMA-I.

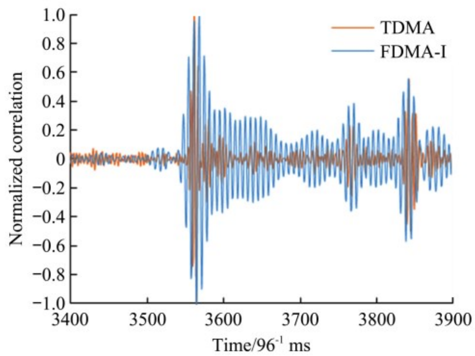
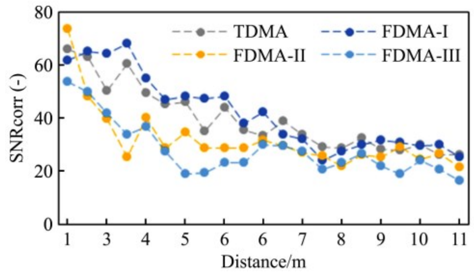


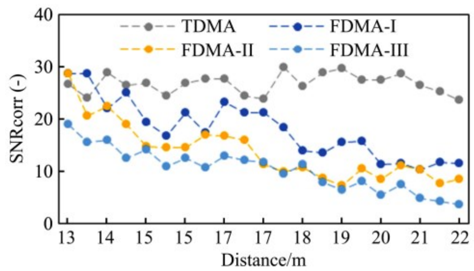
Figure 8 Correlation result of FDMA-I signals and TDMA signals

Figure 9 illustrates the relationship between the carrier frequency and SNRcorr against distance attenuation. The x-axis is the distance from the speaker to the target microphone. Figure 9a shows the SNRcorr results of speaker 2 were located very close to the experiment points of microphones, therefore, the graph shows a similar result for the attenuation effect. It is believed that the TDMA performed similarly to FDMA-I methods because they share the same carrier frequency.

Figure 9b shows the SNRcorr from a long range of the signal transmission, the x-axis is the distance from speaker 4 to the target microphone. Because the experiment condition is set to make the worst situation for channel interference of speaker at a far distance with a speaker at a close distance. The strength of SSSound, with respect to the noise, is described as the larger the SNRcorr, the larger the noise tolerance. Normally, the arrival time of the sound signal is difficult to be detected when SNRcorr value is small. The FDMA method does not show it as competitive compared to TDMA, especially for a long range. The reason is believed to be the interference of SSSound signal as well as the attenuation of high-frequency sound in the air against distance[18] which means the sound pressure level damps as distance increases, and the atmosphere absorption increases as sound frequency elevate.



a. Speaker 2



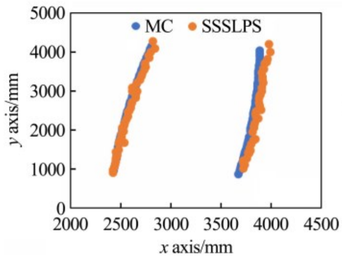
b. Speaker 4

Figure 9 SNRcorr evaluation of TDMA and FDMA at Speaker 2 and Speaker 4

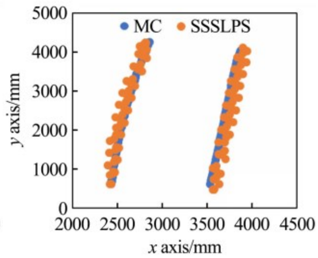
4.2 Dynamic positioning of TDMA and FDMA

The position error for TDMA is (180.3±71.4) mm and the FDMA result is (62.1±22.5) mm. The mean absolute range error of TDMA and FDMA are (92.3±34.5) mm and (41.5±13.5) mm respectively. Cultivation types have different accuracy requirements for a positioning system. For example, there are four planting modes for a strawberry greenhouse: table-top, bench-type, elevated-substrate, and ridge-planting[19], and the corresponding robot movable path widths are 100 cm, 80 cm, 60 cm, and 35 cm, respectively. Assuming the robot's width is 25 cm, the robot can know which furrow is running and its current location in a table-top, bench-type, or elevated-substrate cultivation strawberry greenhouse with the accuracy of the current positioning system. On the other hand, suppose only the proposed positioning system is used to guide the robot’s path in a ridge-planting greenhouse. In that case, the 2D positioning accuracy should reach 5 cm to prohibit the robot will not run on the ridge.

Figure 10a shows the trajectory of FDMA which is similar to the route of TDMA. The measurement of each method was performed four times independently and it can be seen that the FDMA position result of SSSLPS is much overlapped with Motion Capture references coordinates. The position error of the FDMA measurement results has higher accuracy, and the average positioning error is (62.1±22.5) mm. Figure 10b shows the measurements of TDMA that the SSSLPS coordinates have a shifting problem. TDMA time delay problem resulted in a shifting issue of the moving trajectory. It increased the error range as each speaker has an accumulative 250 ms delay for each speaker’s measurement. For moving at a velocity of 300 mm/s, the average positioning error is (180.3±71.4) mm. Concerning the TDMA time delay error with different velocities, a simulation was done from 100 mm/s to 1000 mm/s.



a. FDMA



b. TDMA

Note: MC: Motion capture system

Figure 10 Dynamic movement of FDMA TDMA

Figure 11 illustrates the TDMA simulation result of 2D position error versus the velocity of the moving robot in a similar setting of the dynamic experiment environment. The simulation results showed that the time delay problem of TDMA will increase the positioning error. From the robot velocity of 100 mm/s, the position error is estimated at (68.2±6.0) mm. When the moving speed is at 300 mm/s, the position error is anticipated to be (130.9±20.2) mm assuming the ranging error was following a 25 mm Gaussian distribution. The simulation has excluded the frequency shifting problem and the Doppler shift algorithm for solving the frequency shifting in dynamic positioning. While it can be anticipated that when the robot is moving at a higher speed, the position error will also increase according to the simulation model. It is possible to combine SSSLPS with other localization systems such as inertial measurement units as a hybrid system that our team simulated the improved localization results using the data from the accelerometer and gyroscope[20]. Another possible approach to increase TDMA performance is to increase the update frequency by a shorter sound signal. However, this trail needs to be balanced with the noise tolerance of SSSound.

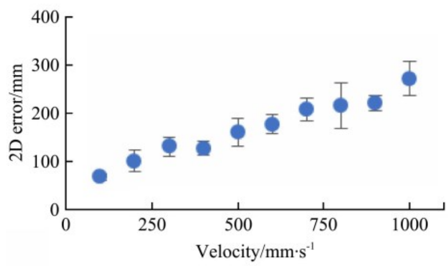


Figure 11 TDMA simulation result of 2D position error with different moving speeds

4 Conclusions

To conclude, the FDMA method suffered complex effects, including overlap signals interference and high-frequency sound damping whilst TDMA has an issue of the time delay for signal transmission. For static measurements, the TDMA achieved an average 12.2 mm positioning accuracy in a greenhouse. The static experiment does not affect by the time delay problem but FDMA has a peak detection error which contributes to the main error of positioning result and also the high-frequency damping problem. For the dynamic experiment, FDMA achieved an average 62.1 mm positioning accuracy. Since TDMA needs to allocate the time slots for each speaker, measuring a distance means the waiting time for a time slot is necessary. It is obvious to see that the TDMA method has a severe time delay shifting problem, while the FDMA method without frequency overlapping does not have such a time delay problem and it is suitable to measure the position of moving agricultural robots. As the objective is to tackle the near-far problem of conventional SSSLPS, this study shows that the TDMA method is suitable for static measurement, whilst the FDMA method is suitable for measuring dynamic objects and controlling moving robots.

Acknowledgements

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