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修士論文

Wireless Communication and Power Transmission Using a Modulated Microwave beam

－変調マイクロ波ビームによる無線電力情報同時伝送－

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Chapter 1　Introduction

1.1　Wireless Power Transmission

Power supply methods have been generally wire transmission methods using power line from power stations and codes from consents. While, communication technology is almost become wireless, such as television, radio, mobile phone and wireless LAN. Therefore, recently, power supply system has been changing from wire into wireless. Today, a lot of research and development about mobile ubiquitous equipments have been studied intensively. Wireless power supply are conducted for short charging time, easier charging, home appliance which can be anywhere, light battery capacity or resources and environment preservation such as reduction of code and harness which are around room and car.[1], [2] Wireless Power Transmission is divided into some parts for the transmission range as in Figure 1.4.

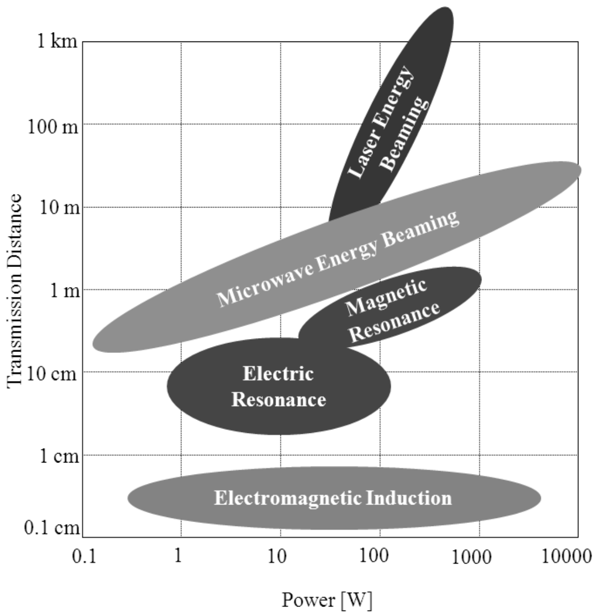


Figure 1.4 Classification of Wireless Power Transmission

Power supplying in short range is generally used electromagnetic induction. Electromagnetic induction is the production of voltage across a conductor moving through a magnetic field. This electromagnetic induction method of wireless power transmission has small power loss but short transmission range. The applications are, for example, passenger's cards of trains and buses and electric money cards.

Secondly, wireless power transmission in middle range is explained. Middle range means about L/D = 1 length, which D is antenna's size and L is transmission length. In the range, we are not able to transmit power effectively using electromagnetic induction method. Instead of the electromagnetic induction method, in the range, we can use strongly-coupled resonance method. The method is new technique and Professor Marin Soljacic et al. at MIT[3] reported in 2006. In the theory, used not electromagnetic wave but electric or magnetic field, the power is transmitted from dielectric or resonating valance bond to the receiver. Because of this advantage such as longer transmission range and higher efficiency than the induction method, the strongly-coupled resonance method receives much attention as a new technique of wireless power transmission.

Finally, there is electromagnetic beam radiation method as technology of wireless power transmission to further range than wavelength. It is generally thought that electromagnetic radiation cannot transmit power sufficiently because the radiation diffuses with the transmission length. However a formation of electromagnetic beam makes the transmission length be extremely longer with small loss. This technology have been mainly focused on the space field, so power transmission to lunar probe using laser[4] and large power transmission from solar power satellite to the ground[5] have studied. Recently there has been interest in wireless power supply of robots and unmanned aircrafts.

1.2 Microwave Wireless Power Transmission

Electromagnetic radiation (EMR) is a form of energy exhibiting wave like behavior as it travels through space.EMR has both electric and magnetic field components, which oscillate in phase perpendicular to each other and perpendicular to the direction of energy propagation. EMR is applied to lots of technologies such as information-communication technology. Table 1.2 shows classifications of frequency of EMR and these applications.

Table 1.2 Classifications of EMR

Wave length	Frequency [Hz]	Name	Applications
10 ~ 1km	30k ~ 300k	Long Frequency (LF)	Aeronautical radio Marine radio
1km ~ 100m	300k ~ 3M	Middle Frequency (MF)	AM radio
100 ~ 10m	3M ~ 30M	High Frequency (HF)	Shortwave broadcast
10m ~ 1m	30M ~ 300M	Very High Frequency (VHF)	FM radio
1m ~ 10cm	300M ~ 3G	Ultra High Frequency (UHF)	Mobile phone Microwave oven
10cm ~ 1cm	3G ~ 30G	Super High Frequency (SHF) Microwave	Satellite broadcasting
1cm ~ 1mm	30G ~ 300G	Extremely High Frequency (EHF) Millimeter wave	Satellite communications
1mm ~ 0.1mm	300G ~ 3T	Submillimeter wave	

Microwaves are electromagnetic waves with wavelength ranging from as long as one meter to as short as one millimeters, or equivalently, with frequencies between 0.3 GHz and 300 GHz. In all cases, microwave includes the entire SHF band (3 to 30 GHz, or 10 to 1 cm) at minimum, with RF engineering often putting the lower boundary at 1 GHz (30 cm), and the upper around 100 GHz (3 mm). Microwave technology is first developed as radar technology in 1940s. The radar uses the characteristics of microwaves which travel in a straight line because of the short wavelength and reflect off an object which has size above the wavelength. After that microwaves have had a wide filed of application because of the advantage of straight traveling and the large transmission capacity of information. Microwaves are applied to mobile phones and satellite communications as transmission signals, microwave ovens using dielectric heat of microwaves, radio astronomy, particle acceleration and medical devices. Then microwave technology has attracted much attention.

Microwave Wireless Power Transmission (MWPT) is first reported by W. C. Brown in 1960s[6], [7]. Since he succeeded microwave power transmission to a helicopter, MWPT is applied to large applications such as Solar Power System in space (SPS) and also small applications such as micro robots which can move with small power because MWPT has long transmission range.

1.3 MWPT to Micro Aerial Vehicle

Conventional transportation systems, for example cars and aircrafts, are able to have long running distances and high mobility with loading some fuels of high energy densities. However it is difficult to replace such abilities to battery's abilities. To run longer without power supply, the systems need larger capacities of charge. Therefore batteries need more mineral resources, the weight of the batteries is larger than that of passengers and loads and the total efficiency become to be lower. To degrease the weigh and load of the batteries, the systems need to be supplied power frequently at the supply station, so techniques of wireless power transmission are necessary. Micro robots, which developed for surveillance and checking of devastated district, medical examination of body and so on, are used. However the robots sometimes cannot move with their size, wire and weight. Without batteries, their duration, size and range of moving are not be regulated. These days ICs, sensors and LEDs have been developed at mW levels, so higher functions devices without batteries are able to be designed and new applications are expected.

Micro Aerial Vehicle (MAV) is a power beaming system and an unmanned aircraft [8] - [15]. With this wireless power transmission system, a battery on a vehicle is charged by receiving a microwave beam while the vehicle is circling above a phased array transmitter. Then, it can fly over the area struck by disaster, for example, continuously without landing and take-off for recharging. **Error! Reference source not found.** shows the schematic of the system developed in our laboratory. It consists of three sub-systems; a transmission system[8], [10], [11], [14], [15], a tracking system[8], [10], [11], [14], [15], and a receiving system[9], [12], [13]. The MAV is tracked using the phase information of pilot signal. Software retro-directive function has been realized through a PC control and a microwave beam is pointed to the MAV using an active phased array. An electric motor for a propeller is driven by the power received on a rectenna array. Rectenna has antenna and RC-DC conversion circuit which converts microwave power to DC power.

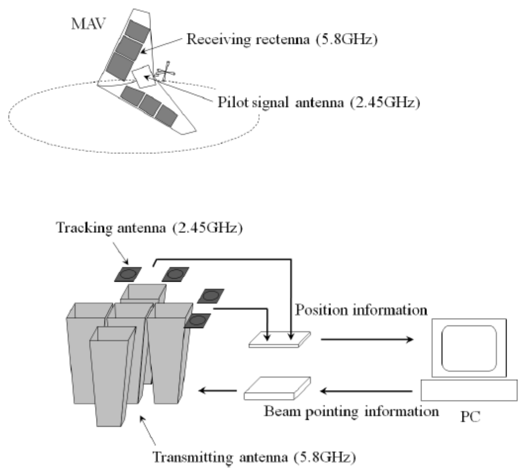


Figure 1.2 Schematic of the MAV system

1.4 Wireless Communication and Power Transmission using Modulated Microwave Beam[16]

As a next step of this research, power transmission while communication between MAV and ground system is suggested. Recently, energy harvesting technology has been studied using radiated radio wave for communication. To take out radio wave as energy is lead to decrease equipment and frequency band width. Moreover, in Radio Law, frequency band of power transmission is not still assigned. However, frequency band for communication was already admitted. Thus, power transmission could be possible by using the radio wave for communication.

Therefore, in previous wireless power transmission system 2.45GHz and 5.8GHz microwave is already used. Then, the microwave can be used as not only power transmission but also communication. In this thesis, 2D tracking system using wireless camera signal and wireless power transmission system using modulated microwave beam basis of above theme is introduced.

In the study of 2D tracking system using wireless camera signal, wireless camera signal for sending picture information, which is taken by the camera on MAV, is treated as a pilot signal. By this treatment, tracking information and picture information are taken out simultaneously on the ground. In the study of power transmitting using modulated microwave, 5.8GHz transmitted microwave is used as carrier signal for communication. This is, not only power transmitting but also communication to MAV. In the future, control for MAV from ground will be possible by this study.
Figure 1.4 shows a concept of wireless communication and power transmission using a modulated microwave beam.

Figure 1.3 Concept of Wireless Communication and Power Transmission Using a Modulated Microwave Beam.

Chapter 2 Communication System

2.1 Theory of Communication System[16]-[18]

When information is recorded and sent by wireless, processing of modulation and demodulation is executed. Radio wave, whose waveform is sin wave, is excreted some changes at transmitting system. Then, at receiving system, the changes of wave are read out. Information-communication is possible through this process. To excrete change into transmitted radio wave, which is carrier signal, is called “Modulation” and to read out information from transmitted signal is called “Demodulation”. Analog modulation and digital modulation are known as basic modulation methods, though these modulation methods are same theory. The ways of modulations are three patterns: amplitude modulation, frequency modulation and phase modulation. Frequency modulation and phase modulation are collectively called angle modulation because these modulation change angular frequency of carrier signal. In following sections, theories of amplitude modulation and angle modulation are described. However, only frequency modulation is introduced on angle modulation.

2.2 Amplitude Modulation (AM)

Amplitude modulation was used in an electric communication field for the first time. In amplitude modulation method, amplitude of transmitted signal wave, for instance sound information, is changed. This is, amplitude of alternating current (AC) waveform is changed. Recently, amplitude modulation is still used as AM broadcast in a middle frequency band. In this section, theory of AM is introduced.

2.2.1 Theory of Amplitude Modulation

Figure 2.1 shows construction of AM waveform. In Fig 2.1, a function of carrier waveform is defined as $f(t)$. The function $f(t)$ is given by

$$f(t) = A\cos\omega_c t, \qquad \omega_c = 2\pi f_c, \qquad f_c = \frac{1}{T_c}. \tag{2.1}$$

Here, A is amplitude of carrier wave and f_c is frequency of carrier wave.

A function of signal waveform is defined as $B(t)$. The function $B(t)$ is given by

$$B(t) = mA\cos\omega_s t, \qquad \omega_s = 2\pi f_s, \qquad f_s = \frac{1}{T_s}. \tag{2.2}$$

Here, mA is amplitude of signal waveform and m is an amplitude modulation factor; value of m is less than 1.0.

From Eq. (2.1) and (2.2), the equation of AM waveform is expressed as

$$f(t) = A(1 + m\cos\omega_s t)\cos\omega_c t. \tag{2.3}$$

Eq. (2.3) is formula of AM waveform. Finally, modulated signal wave is transmitted to receiving antenna.

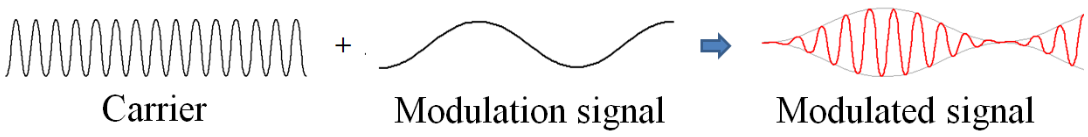


Figure 2.1 Construction of AM waveform.

2.2.2 Frequency Spectrum of AM

Using a formula of trigonometric function, Eq. (2.3) can be expressed as

$$f(t) = A\cos\omega_c t + \frac{mA}{2}\cos(\omega_c + \omega_s)t + \frac{mA}{2}\cos(\omega_c - \omega_s)t \tag{2.4}$$

As shown in Eq. (2.4), AM waveform is consisted of three frequency components. Frequency spectrum is shown in Figure 2.2.

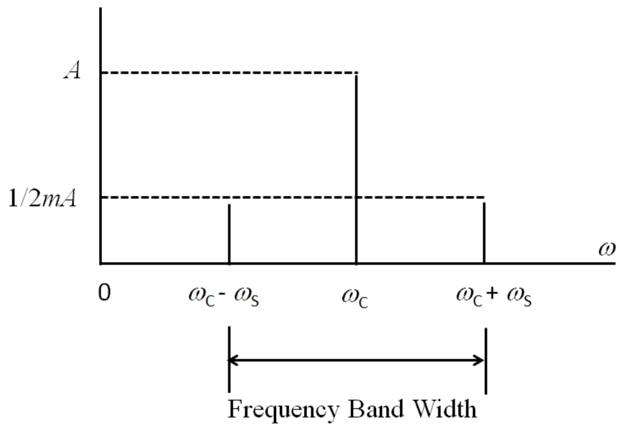


Figure 2.2 Band width of AM

In Fig.2.2, center of spectrum is frequency of carrier waveform, right side of spectrum is frequency of up side band, and left side of spectrum is frequency of low side band. Actually, transmitted signal wave has some frequency components. Here, a maximum frequency component is treated as f_s . In this case, a spectrum distribution of AM wave is in range from $\omega_c - \omega_s$ to $\omega_c + \omega_s$. Thus, the band width of frequency, which the AM wave includes, is $2f_s$.

2.3 Frequency Modulation (FM)

Frequency modulation (FM) was developed after AM. In frequency modulation method, a frequency of AC waveform, which is corresponded an intensity of signal wave, is changed with keeping amplitude of the wave constant. In this section, theory of FM is introduced.

2.3.1 Theory of Frequency Modulation

AC waveform as a radio wave is determined by amplitude and frequency. Frequency modulation is to excrete change frequency of the wave for sending information signal instead of changing amplitude. Figure 2.3 shows construction of FM waveform.

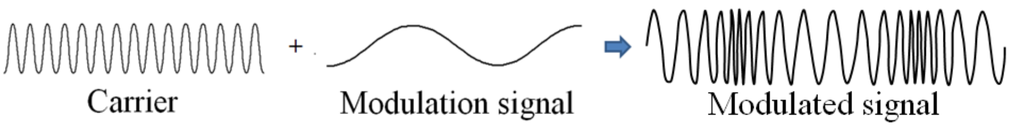


Figure 2.3 Construction of FM waveform

In Fig.2.3, a frequency of signal wave is one of frequency component of transmitted information signal $f_s = 1/T_s$. Amplitude of this waveform is defined as Δf . This means that a frequency of radio wave is shifted in range of $f_c \pm \Delta f$. f_c is frequency of carrier signal. Then, angler frequency of radio wave ω is expressed as

$$\omega = \omega_c + \Delta\omega \cos \omega_s t, \qquad \omega_c = 2\pi f_c, \qquad \Delta\omega = 2\pi \Delta f \ . \tag{2.5}$$

FM wave has angler frequency like Eq. (2.5).

Figure 2.4 shows a graph for developing the formula of FM.

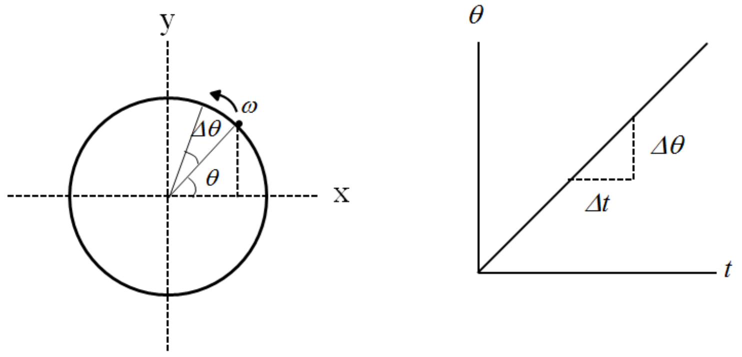


Figure 2.4 Graph of developing the expression for FM.

Given minor time Δt as shown in Fig.2.4, angle θ is expressed with gradient ω as

$$\Delta\theta = \omega\Delta t, \qquad \omega = \frac{\Delta\theta}{\Delta t} \rightarrow \frac{d\theta}{dt} \qquad \therefore \theta = \int \omega dt\ . \tag{2.6}$$

Eq. (2.6) is substituted for Eq. (2.5). Integral constant is zero. θ is

$$\theta = \omega_c t + \frac{\Delta\omega}{\omega_s}\sin\omega_s t\ . \tag{2.7}$$

From Eq. (2.7), formula of FM wave cam be expressed as

$$f(t) = A\cos(\omega_c t + m'\sin\omega_s t), \qquad m' = \frac{\Delta\omega}{\omega_s} = \frac{\Delta f}{f_s}\ . \tag{2.8}$$

This is formula of FM wave. Here, *m'* is frequency modulation factor.

2.3.2 Frequency Spectrum of FM

Using a formula of trigonometric function, Eq. (2.8) can be expressed as

$$\begin{aligned} f(t) &= A\{\cos\omega_c t\cos(m\sin\omega_s t) - \sin\omega_c t\sin(m\sin\omega_s t)\} \\ &= AJ_0(m)\cos\omega_c t + A\sum_{n=1}^{\infty} J_{2n}(m)\left[\cos(\omega_c + 2n\omega_s)t + \cos(\omega_c - 2n\omega_s)t\right]. \\ &\quad + A\sum_{n=1}^{\infty} J_{2n-1}(m)\left[\cos\{\omega_c + (2n-1)\omega_s\}t - \cos\{\omega_c - (2n-1)\omega_s\}t\right] \end{aligned} \tag{2.9}$$

Eq. (2.9) is frequency spectrum of FM. Here, J_n is n-th degree Bessel function.

Chapter 3 Tracking System using Wireless Camera Signal

3.1 System Overview [16]

In this section, a concept of the tracking system is introduced. To realize high efficiency wireless power transmission, detecting an MAV position is very important element because of pointing a microwave beam toward the MAV with accuracy. In this research, software retro-directive function is adopted as the tracking system. "Phase of microwave" which is used at the phased array system is utilized to the tracking system. There are some advantage points of adopting it, for example, the theory is simple, the system can be compact, and the system readiness is fast.

At the tracking system, the software retro-directive function is under development. This system receives a pilot signal of 2.45GHz microwave sent from the MAV and analyzes its current position using the phase difference.

3.2 Theory of Tracking System

First, if there are two antennas with spacing *d*, the antennas receive the incident signals, which are expressed as

$$\boldsymbol{E}_0 = E_0 \exp\ j\omega t \tag{3.1}$$

$$\boldsymbol{E}_1 = E_1 \exp\ j(\omega t + \varphi_1) \tag{3.2}$$

Here φ_1 is the relative phase difference between these two antennas. When the free-space wavenumber is k, and the incident angle of a pilots signal is α, the phase difference becomes as

$$\varphi_1 = kd \sin\alpha \tag{3.3}$$

After this, the simple model which is expressed as Figure3.1 is assumed. If two antennas, one $+\varphi_0$ phase shifter, two dividers, one mixer, and three detectors are combined like this figure, the waves are expressed as

$$\boldsymbol{E}_0 = E_0 \exp\ j(\omega t + \varphi_0) \tag{3.4}$$

$$\boldsymbol{E}_1 = E_1 \exp\ j(\omega t + \varphi_1) \tag{3.5}$$

After phase shifting, the microwave is divided into two waves at each line, and then, by a power mixer, they are combined into the composite wave whose power depends on the amplitudes of two input waves. The composite wave is expressed as follow

$$\boldsymbol{P}_{com} = (\boldsymbol{P}_0^2 + \boldsymbol{P}_1^2)^2 \tag{3.6}$$

Applying the trigonometric functional equation to Eq. (3.4)

$$P_{com} = P_0 + P_1 + 2\sqrt{P_0 P_1}\cos(\varphi_0 - \varphi_1) \quad (3.7)$$

Finally, detectors rectify power of the waves into voltage. The output voltage from the detector is liner proportional to input power, so the following equation is obtained.

$$V_{com} = V_0 + V_1 + 2\sqrt{V_0 V_1}\cos(\varphi_0 - \varphi_1) \quad (3.8)$$

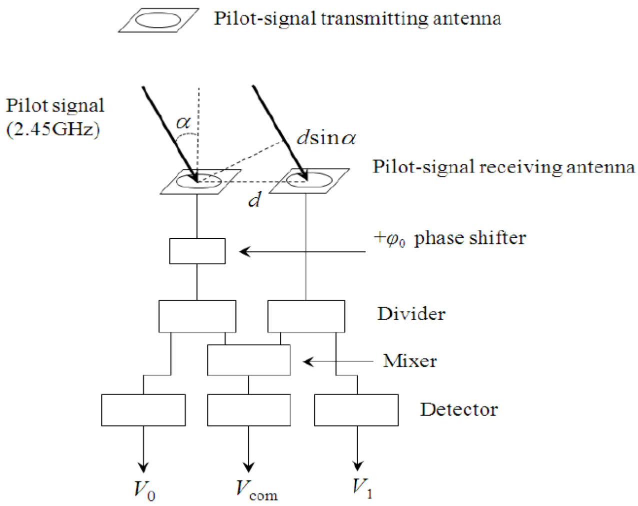


Figure3.1 Simple model of tracking system

If $+\varphi_0$ phase shifter is not combined, Equation(3.6) becomes as

$$V_{com} = V_0 + V_1 + 2\sqrt{V_0 V_1}\cos\varphi_1 \quad (3.9)$$

In both cases $\pm\varphi_1$, the composite wave voltages become the same value and are not differentiated, which is represented in Figure3.2.

$$V_{com}(\varphi_1) = V_{com}(-\varphi_1) \quad (3.10)$$

This is the reason for adding a certain phase shift to the line-0. In the previous study, φ_0 is decided as $\pi/2$, and Equation(3.6) is given by

$$V_{com} = V_0 + V_1 + 2\sqrt{V_0 V_1}\sin\varphi_1 \quad (3.11)$$

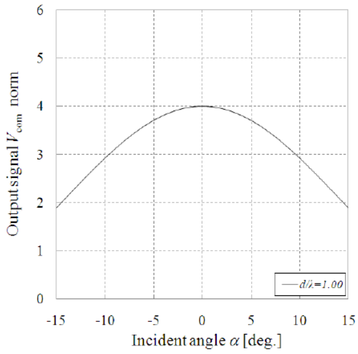
Figure3.3 represents this equation. As will be find from this figure, there is a one-to-one correspondence between the output signal V_{com} and the incident angle of a pilots signal α. Therefore, if the output signal is measured, the incident angle can be detected.

Actually, however, output signals V_0 and V_1 are affected by individual differences of each component, so they do not fulfill the Equation(3.9). Therefore, fitting coefficients η_0 and η_1 are introduced. If fitting coefficients η_0 and η_1 are used, Equation(3.9) becomes as

$$V_{com} = \eta_0 (V_0 + V_1 + 2\eta_1 \sqrt{V_0 V_1} \sin \varphi_1) \tag{3.12}$$

If the pilot signal transmitting antenna is far from two pilot signal receiving antennas, the receiving signal E_0 and E_1 are almost the same level of intensity. The value of V_0 is largely similar to V_1, and Equation(3.10) is given by

$$V_{com} = 2\eta_0 V_1 (1 + 2\eta_1 \sin \varphi_1) \tag{3.13}$$



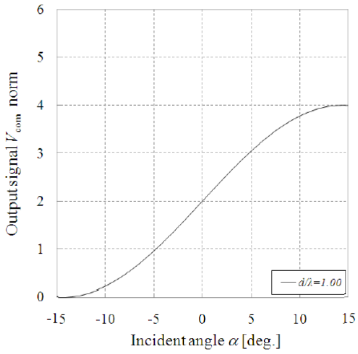


Figure3.2 V_{com} without any insertion phase to line-0 (Left).

Figure3.3 V_{com} with $+\pi/2$ phase shifting at line-0 (Right)

3.3 Tracking System using Wireless Camera Signal

As already mentioned in Theory of Tracking System section, the position of the MAV was detectable using 2.45GHz microwave as a pilot signal from a MAV.

In this section, new tracking system, which is not only tracking but also getting picture information from MAV using a wireless camera simultaneously, is introduced. A wireless camera is set as a pilot signal oscillator on a MAV. The wireless camera radiated carrier signal with 2.45GHz frequency modulated microwave for communication. The receiver for communication was set on the ground aside from tracking antenna (Figure 3.4). Thus, it's possible to get both position and picture information simultaneously with only 2.45GHz frequency band because picture signal plays a pilot signal role in the tracking system.

The 2D tracking experiment using wireless camera as a microwave oscillator was done. Then, monopole antenna of a wireless camera was changed into circular polarized antenna not to be dependent on yaw angle. The coaxial cable was used to connect wireless camera and circular polarized antenna for preventing radiation from cable.

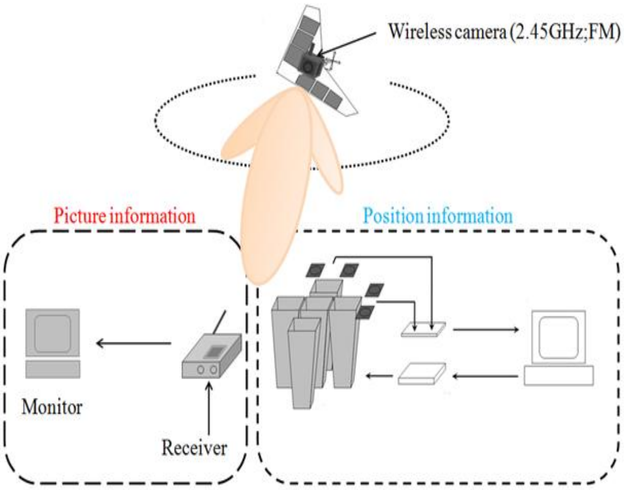


Figure 3.4 Tracking system using wireless camera signal.

3.4 Experimental Setup and Result

Tracking experiments were done using above theory and equipments. The MAV model on-board a wireless camera, which radiated 2.45GHz frequency-modulated pilot signal, was used for 2D tracking experiment of a circling target. The circular polarized antenna with the camera was set at an altitude of 1,500mm from tracking antennas on the ground. Figure 3.5 shows picture of experiment. It was rotated by an electric motor. In this experiment, the maximum incident angle of 9deg was set from the point of view the integration of the tracking and the transmitting system. The maximum steering angle was 9deg. in transmitting system. Figure 3.6 shows the schematic of definition of 2D tracking experiment.

The pilot signal receiving antennas are set up at height of 50mm from the aperture plane of the transmitting antenna array as shown in Figure3.7. And the distance between two antennas d_1 was set to 122mm (=λ). By this setup of tracking antenna, the incident angle between -14.5deg. to +14.5deg. has come to be detected.

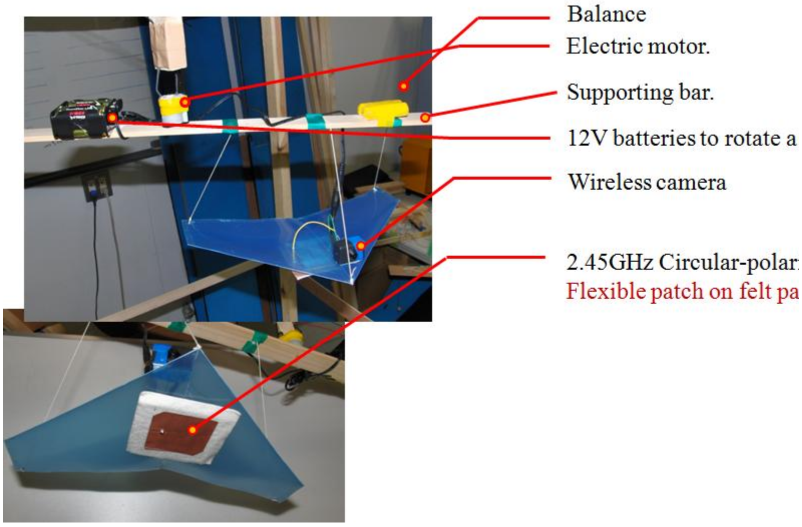


Figure 3.5 **Picture of 2D tracking experiment using wireless camera**

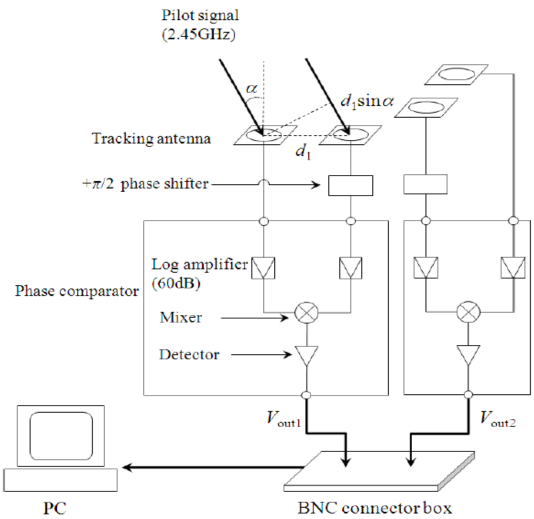


Figure 3.6 **Schematic of definition of 2D tracking experiment.**

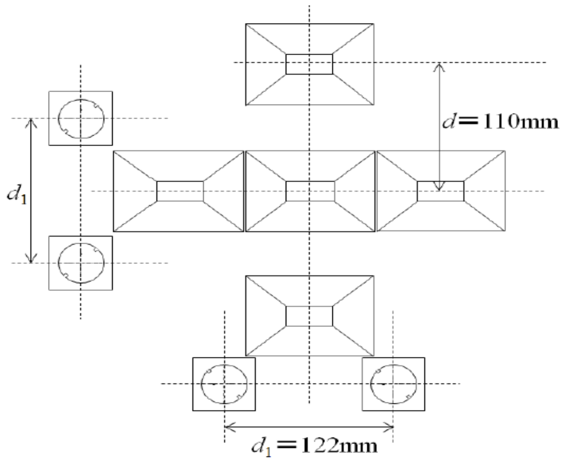


Figure 3.7 The pilot signal receiving antennas.

In addition, the phase comparator “Arumo Tech – FS00T2703” is installed in the tracking system. This device has two RF input ports and one DC output port. The DC signal is output from the port in response to the phase difference of two input microwave. The internal circuit of this phase comparator is shown in Figure3.8.

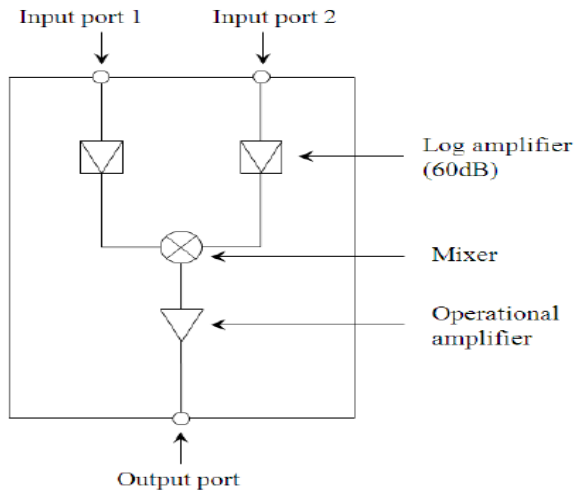


Figure 3.8 Internal circuit of phase comparator.

The microwaves which is come from input ports are amplified +60dB by log amplifiers to uniform the amplitude of two signals. It is because the powers of each input waves have individual differences which are derive from the individual difference of tracking antenna’s polarization shape as explained. Then two input signals are combined at the mixer and normalized at the operational amplifier. The connector shape of input port and output port is BNC-J, but input ports have to be SMA-J. Thus, the BNC-J/SMA-J conversion connectors are installed at each input port. The specification of this phase comparator is follow; the frequency range is from 2.3GHz to 2.5GHz, the detectable phase difference is from 10deg. to 170deg., and the power range of input signal is from -60dBm to -10dBm.

The relationship between the incident angles of pilot signal α and the output voltage V_{out} was decided as follows.

$$V_{out} = \eta_1 + \eta_2 \sin(kd \sin \alpha) \tag{3.14}$$

Here η_1 and η_2 are fitting coefficients. The value of η_1 and η_2 were calculated from the measurement result which is shown in Figure 3.9. The pilot-signal transmitting antenna is set at height of 1500mm. From these results, the fitting coefficients η_1 and η_2, η_3 and η_4 are decided as

x-direction: $\eta_1 = 0.93$, $\eta_2 = -0.76$

y-direction: $\eta_3 = 0.91$, $\eta_4 = -0.78$

And they are set at the altitude of 1070mm and the rotation radius was 169mm which are corresponding incident angle was 9.0deg.. Figure3.10 shows the estimated incident angles using the correlation shown in Figure3.9. The error was $-3.22\text{deg} \leqq \alpha_{rad} \leqq 2.22\text{deg}$ in radial-direction and was $-2.42\text{deg} \leqq \alpha_{azi} \leqq 4.97\text{deg}$ in azimuth-direction.

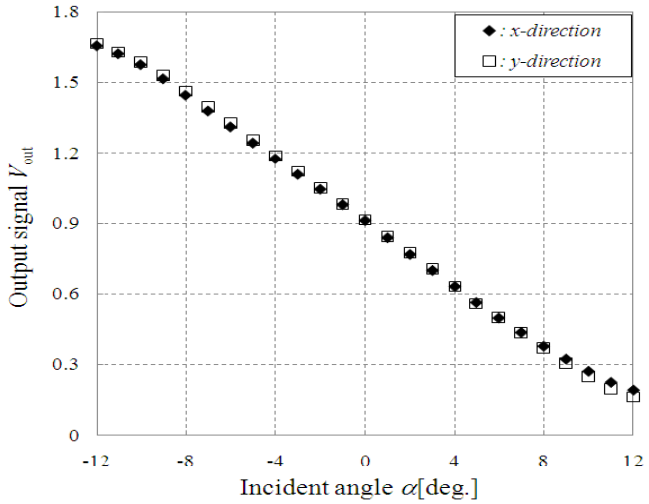


Figure 3.9 Relationship between incident angles and output voltage.

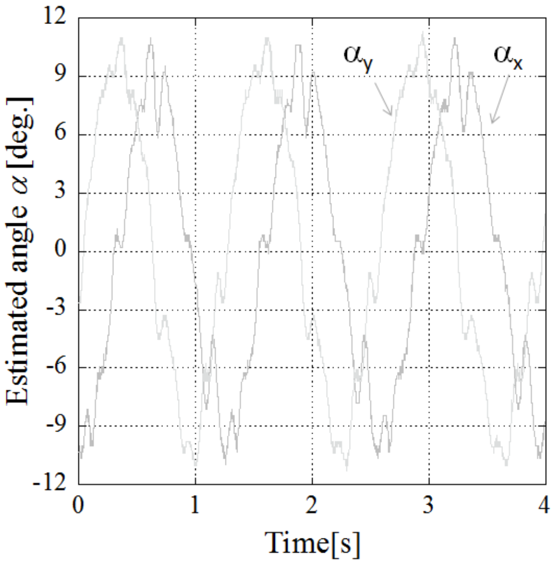


Figure 3.10 The estimated incident angles using the correlation.

The reason of the error is that phase is out of alignment because of frequency modulation. Moreover, input power isn't enough because antenna of wireless camera is changed monopole antenna into circular polarized wave antenna. Thus loss of impedance mismatching between feeder and electric circuit is bigger.

However, circling motion of wireless camera can be detected. Thus, the position of MAV is almost detected and picture information from wireless camera can be received. Figure 3.11 shows picture of experiment when 2D tracking for MAV and picture information, which is taken by wireless camera, is received simultaneously.

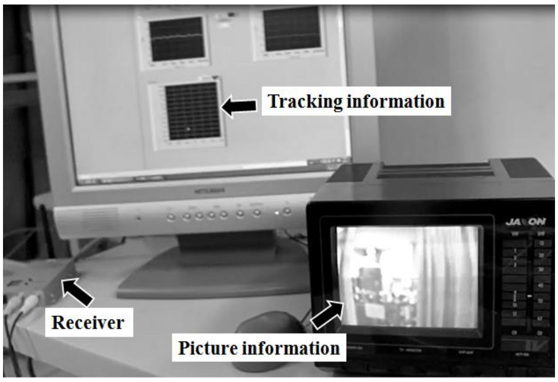


Figure 3.11 Picture of experiment when 2D tracking for MAV and picture information.

Chapter 4 Transmitting System using Modulated Microwave Beam

4.1 Overview of Transmitting System [16]

At this transmitting system, 5.8GHz microwave is used as a carrier wave and the phased array function is adopted. The active phased array system can steer a microwave beam not mechanically but electrically, thus it is realized to point a microwave beam toward the target moving quickly.

4.2 Theory of Transmitting System

In this section, a basic theory of the phased array which was adopted as the transmitting system is introduced. At the phased array system, synchronizing phases is a key point to get a high efficiency microwave beam.

4.2.1 Assumption for the signal patterns

First, for simplicity, if there are two point wave sources with spacing *d*, which are in the coordinate phase, electromagnetic field radiated from one point wave source is

$$E = E_0 \exp(kr) \tag{4.1}$$

Here *k* is the free-space wave number.

$$k = 2\pi / \lambda \tag{4.2}$$

And then the composite electromagnetic field radiated from these two point wave sources are expressed as

$$E_{com} = E_1 \exp(ijr_1) + E_2 \exp(ijr_2) \tag{4.3}$$

The condition for maximizing this composite field amplitude is given by

$$k(r_1 - r_2) = 2n\pi \tag{4.4}$$

Assuming that the field is sufficiently far from the two point wave sources as Figure4.1 show, it is approximated with the spacing *d* and angle α with the vertical axis in the following form

$$kd \sin\alpha = 2n\pi \tag{4.5}$$

Or, replacing , Equation(4.5) is rewritten as follows

$$d \sin\alpha = n\lambda \tag{4.6}$$

Now if the wave source phase is shifted by θ against the other wave source, the amplitude of the composite electromagnetic field is

$$E_{com} = E_1 \exp(ijr_1) + E_2 \exp(i(jk_2 + \theta)) \tag{4.7}$$

The maximizing condition is similar to the case of above

$$kd \sin\alpha = 2n\pi + \theta \tag{4.8}$$

In order to maximizing the electromagnetic field at an angle α with the vertical axis, setting n = 0, the phase to shift is expressed as following form

$$\theta = kd \sin\alpha \tag{4.9}$$

Taking into account that θ varies from $-\pi$ to π, Equation (4.9) becomes

$$-\arcsin(\lambda/2d) \le \alpha \le \arcsin(\lambda/2d) \tag{4.10}$$

In this way the steering angle interval can be determined from the wave length λ and the antenna spacing d.

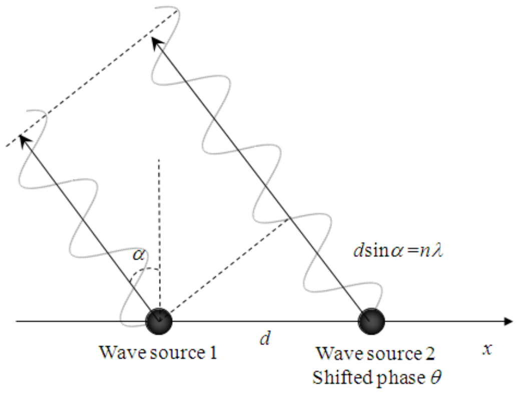


Figure4.1 Simple model of two wave source

4.2.2 Microwave beam control[8]

In this section, the way of steering microwave beam is introduced. The method was already suggested by Mr.Ozawa study [8]. Figure 3.2 shows distribution of five antennas with antenna spacing d. The simulated graphs represent the simulated power distributions. The power values were normalized by the maximum value in these four cases. In these graphs, the irradiating points are colored red to be easily recognized. Figure 3.3 shows radiation field from 2D five-element antenna array in measurement and calculation.

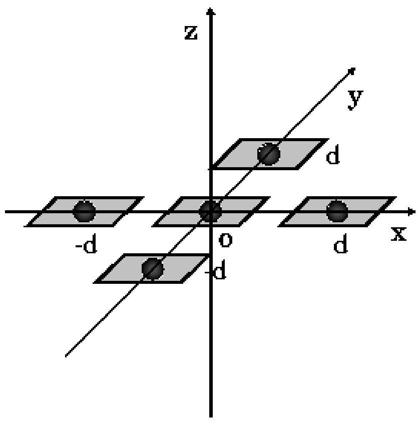
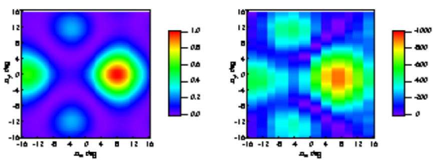
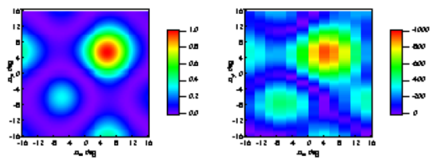


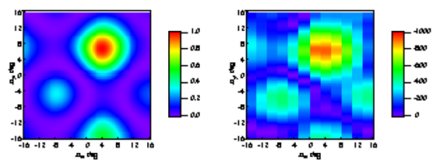
Figure 4.2 Distribution of antennas with antenna spacing d.



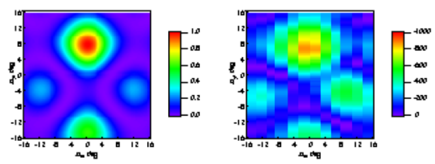
(a) Irradiation point is (160, 0, 1040)



(b) Irradiation point is (113, 113, 1040)



(c) Irradiation point is (80, 139, 1040)



(d) Irradiation point is (0, 160, 1040)

Figure 4.3 Radiation field from five-element antenna array in measurement and calculation

4.3 Transmitting System using Modulated Microwave Beam

The above theory, transmitting system can steer microwave beam for target by phased array system. In this section, discussion of adopting communication system into previous transmitting system, which is for not only supplying microwave power but also communicating with target without adding other device, is introduced.

4.3.1 Consideration for modulating 5.8GHz transmitted microwave beam

As has been mentioned in Chapter 2, communication system needs modulation technology. There are some methods of modulation, such as AM/ASK, FM/FSK and PM/PSK. With adopting modulation into transmitting beam, beam area of transmitting microwave might be different with previous beam area. If beam area is changed, an efficiency of power transmitting system is also different. By adopting modulation system, the efficiency of previous power transmitting must not be decrease. Thus, modulation pattern should be discussed which pattern is optimum for power transmitting system. Therefore, the beam area of transmitting microwave is estimated using numerical simulation by FDTD when transmitting beam is amplitude and frequency modulated. Moreover, the beam area should be discussed when transmitted beam is steered and not because this transmitting beam can be steered by phased array system.

4.3.2 FDTD[21]

The FDTD method, introduced by Yee in 1966[?], was the first technique in this class, and has remained the subject of continuous development. Since 1990, when engineers in the general electromagnetic community became aware of the modeling capabilities afford by FDTD and related techniques, the interest in this area has expanded well beyond defense technology.

There are seven primary reasons for the expansion of interest in FDTD and relates computational solution approaches for Maxwell's equations:

1. *FDTD uses no linear algebra.* Being a fully explicit computation, FDTD avoids the difficulties with linear algebra that limit the size of frequency-domain integral-equation and finite-element electromagnetic models to generally fewer than 10^6 electromagnetic field unknowns. FDTD models with as many as 10^9 field unknowns have been run; there is no intrinsic upper bound to this number.
2. *FDTD is accurate and robust.* The sources of error in FDTD calculations are well understood, and can be bounded to permit accurate models for a very large variety of electromagnetic wave interaction problems.
3. *FDTD treats impulsive behavior naturally.* Being a time-domain technique, FDTD directly calculates the impulse response of an electromagnetic system. Therefore, a

single FDTD simulation can provide ultrawideband temporal waveforms or the sinusoidal steady-state response at any frequency within the excitation spectrum.

4. *FDTD treats nonlinear behavior naturally.* Being a time-domain technique, FDTD directly calculates the nonlinear response of an electromagnetic system.
5. *FDTD is a systematic approach.* With FDTD, specifying a new structure to be modeled is reduces to a problem of mesh generation rather than the potentially complex reformulation of an integral equation. For example, FDTD requires no calculation of structure-dependent Green functions.
6. *Computer memory capacities are increasing are increasing rapidly.* While this trend positively influenced all numerical techniques, it is of particular advantage to FDTD methods, which are founded on discrediting space over a volume, and therefore inherently require a large random access memory.
7. *Computer visualization capabilities are increasing rapidly.* While this trend positively influences all numerical techniques, it is of particular advantage to FDTD methods, which generate time-marched arrays of field quantities suitable for use in color videos to illustrate the field dynamics.

FDTD and related space-grid time-domain techniques are direct solution methods for Maxwell's curl equations. These methods employ no potentials. Rather, they are base on volumetric sampling of the unknown electric field vector ***E*** and magnetic field vector ***H*** within and surrounding the structure of interest, and over a period of time. The sampling in space is at sub-wavelength (sub-l0) resolution set by the user to properly sample the highest near-field spatial frequencies thought to be important in the physics of the problem. Typically, 10 to 20 samples per l0 are needed. Sampling in time is selected to ensure numerical stability of the algorithm. Overall, FDTD and related techniques are marching-in-time procedures that simulate the continuous actual electromagnetic waves in a finite spatial region by sampled-data numerical analogs propagating in a computer data space. Time-stepping continuous as the numerical wave analog propagates in the space lattice to casually connect the physics of the modeled region. For simulations where the modeled region must extend to infinity, absorbing boundary conditions (ABCs) are employed at the outer lattice truncation planes. ABCs ideally permit all outgoing numerical wave analog to exit the computation space with negligible reflection. Phenomena such as induction of surface currents, scattering and multiple scattering, aperture penetration, and cavity excitation are modeled time-step by time-step by the action of the numerical analog to the curl equations. Self-consistency of these modeled phenomena is sampling process. In fact, the goal is to provide a self-consistent model of the mutual coupling of all of the electrically small volume cells constituting the structure and its neat field, even if the structure spans tens of l0 in three dimensions and there are hundreds of millions of space cells.

Time-stepping is continued until the desired late-time pulse response is observed at the field points of interest. For linear wave interaction problems, the sinusoidal response at these field points can be obtained over a wide band of frequencies by discrete Fourier transformation of the computed field-versus-time waveforms at these points. Prolonged "ringing" of the modeled requires a combination of extending the computational window in time and extrapolation of the windowed data before Fourier transformation.

4.4 Numerical Setup of Modulated Transmitted Microwave

At the previous transmitting system, 5.8GHz microwave beam is formed by five-element horn antenna. Thus, a feature of this microwave beam is evaluated using numerical simulation when the microwave beam is modulated. Here, in this simulation modeling of antenna isn't considered. Therefore modulated microwave beam, which is radiated from five-element point radio source, is calculated. The kind of modulation is amplitude modulation (AM) and frequency modulation (FM). Important parameter on this power transmitting system is beam width, intensity of an electric field and band width. The variations of these parameters are discussed because of modulated transmitted microwave.

A calculation condition is mentioned as follows. Figure 4.2 shows a picture of calculation model. Each parameter in this numerical simulation is introduced. An interval of cell (dx, dy, dz) is $\lambda/10$ (=0.0517[cm]) and number of cell (n_x, n_y, n_z) is 400. This means that actual scale is around 206[cm] in each side. Moreover, time resolution dt, which is satisfied Courant-Friedrichs-Lewy condition, is 9.9×10^{-12}[sec.]. Total calculation time step is 1000step. Five wave sources are set as shown in Fig.4.2. The center wave source is on (x, y, z) = (200, 200, 2). The distance of wave sources is $\lambda/2$. Microwave is modulated by changing excitation of each wave source. In this time, observation point of z is 312[cell] = 160[cm].

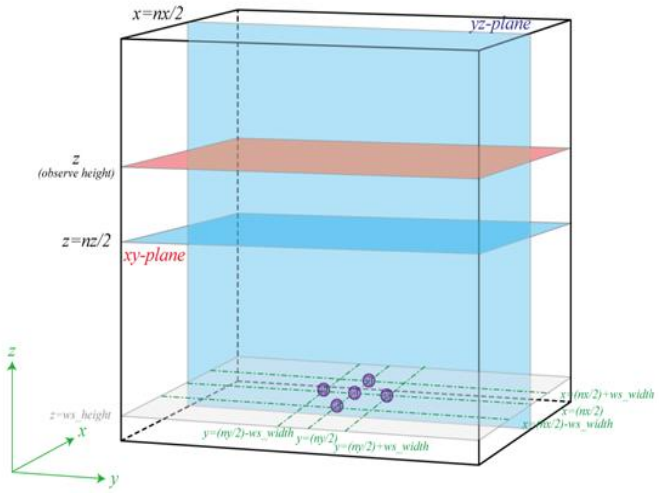


Figure 4.4 Calculation Model

In Fig. 4.4, one-dimensional profile of microwave beam in Z-X plane is shown like Figure4.5. As shown in Fig.4.5, FWHM can be determined from the graph. The FWHM is treated as radius of microwave beam. Thus, beam area can be calculated from the FWHM.

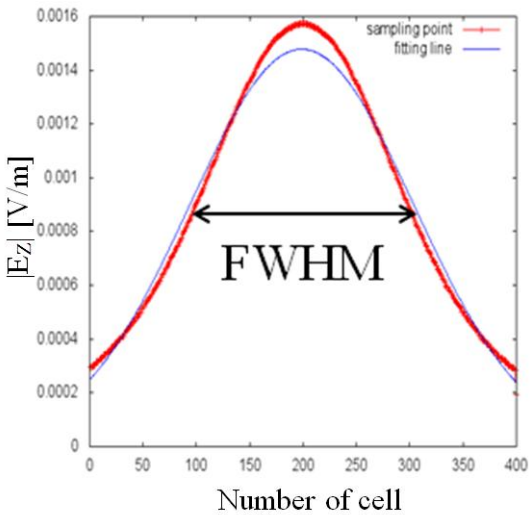


Figure 4.5 Profile of microwave beam in Z-X plane at height of 206[cm].

4.5 Result of Numerical Simulation of Modulated Microwave

In this section, results of calculated beam area with amplitude and frequency modulation are shown.

4.5.1 Amplitude Modulation

Calculation results are shown when microwave is amplitude-modulated.
Here, formula of amplitude modulation is mentioned. A carrier wave V_c and signal wave V_s is expressed as Equation (4.11).

$$\begin{aligned} V_c &= V_{cm} \sin 2\pi f_c t \\ V_s &= V_{sm} \cos 2\pi f_s t \end{aligned} \tag{4.11}$$

With these Equations, modulation wave is

$$\begin{aligned} v_{am} &= (V_s + V_{cm}) \sin 2\pi f_c t \\ &= (V_{sm} \cos 2\pi f_s t + V_{cm}) \sin 2\pi f_c t \\ &= V_{cm} \sin 2\pi f_c t + \frac{V_{sm}}{2} \sin 2\pi (f_c - f_s) t + \frac{V_{sm}}{2} \sin 2\pi (f_c + f_s) t \end{aligned} \tag{4.12}$$

Taking amplitude modulation factor $m = V_{sm}/V_{cm}$ into Equation (4.12), modulation wave becomes

$$\begin{aligned} v_{am} &= (V_{sm} \cos 2\pi f_s t + V_{cm}) \sin 2\pi f_c t \\ &= V_{cm} (m \cos 2\pi f_s t + 1) \sin 2\pi f_c t \end{aligned} \tag{4.13}$$

In an Eq. (4.13), frequency of signal wave f_s and modulation factor m can be coordinate. m can run less than 1.0. if m is more than 1.0, signal can't be demodulated. Therefore, generally, m has value less than 1.0. In this research, the variation of beam area is evaluated by changing these two parameters.
Firstly, most optimum value of m and f_s should be estimated. Then, Figure 4.6 is result of intensity of electric field in Z-direction $|E_z|$ in each value of m and f_s. The value of m and f_s is used when beam area of transmitted microwave is discussed.

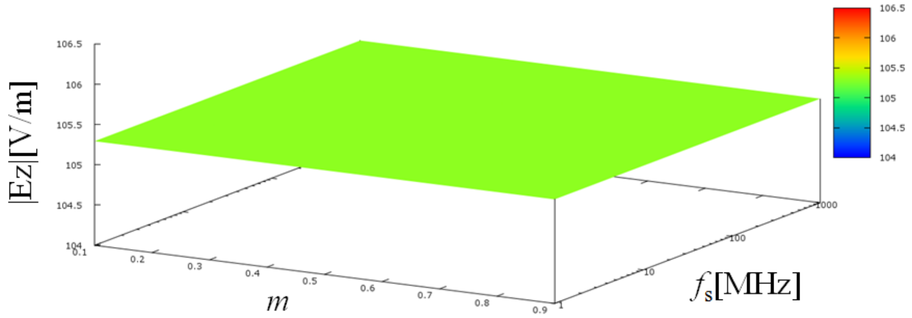


Figure 4.6 **The relation between |Ez| and m,f_s.**

As shown in Fig.4.6, the value of |Ez| doesn't depend on parameter of m and f_s.
Next, an evaluation beam area is done using a result of Fig.4.6. The result of variation for beam area is shown in Figure 4.7 with changing frequency of signal wave f_s. Here, the value of m is 0.9 because of matching condition with FM.

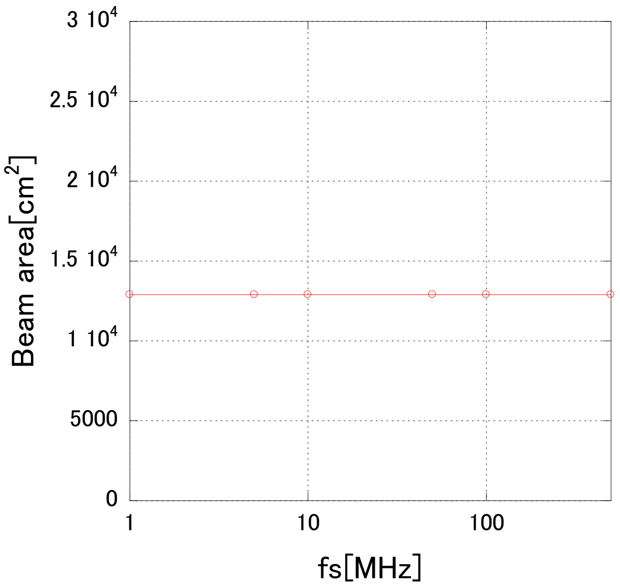


Figure 4.7 **The variation of beam area in each frequency of signal wave f_s.**

As shown in Fig. 4.7, beam area is not different in each f_s. Beam area is 1.29×10^4 [cm^2] when transmitted beam is not modulated. Thus, compared to non-modulate beam area, beam area is same value.

4.5.2 Frequency Modulation

Calculation results are shown when microwave is frequency-modulated.

Formula of frequency modulation is expressed using frequency modulation factor *m'*, carrier frequency f_c and signal f_s as an Equation (4.14)

$$v_{fm} = V_{cm}\cos(2\pi f_c t + m'\sin 2\pi f_s t)\,,\quad m' = \frac{\Delta\omega}{\omega_s} = \frac{\Delta f}{f_s} \tag{4.14}$$

As AM is discussed, firstly, most optimum value of *m'* and f_s should be estimated. The result is shown in Figure 4.8.

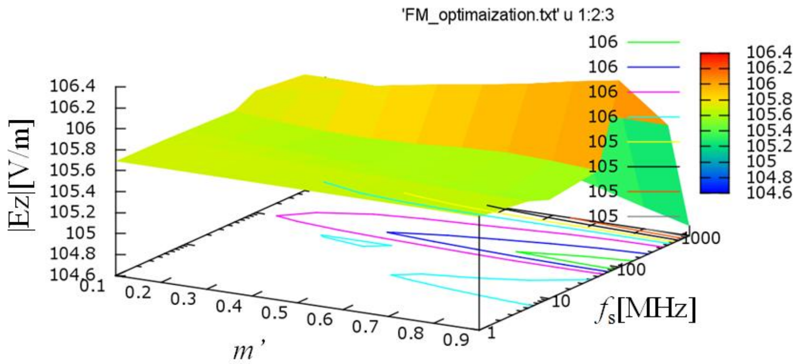


Figure 4.8 The relation between |Ez| and *m'*, f_s.

As shown in Fig.4.8, the value of |Ez| is maximum when *m'* is 0.9 and f_s is 100[MHz]. Therefore, *m'*=0.9 is used in following discussion of beam area.

Result of variation for beam area is shown in Figure 4.9 with changing frequency of signal wave f_s.

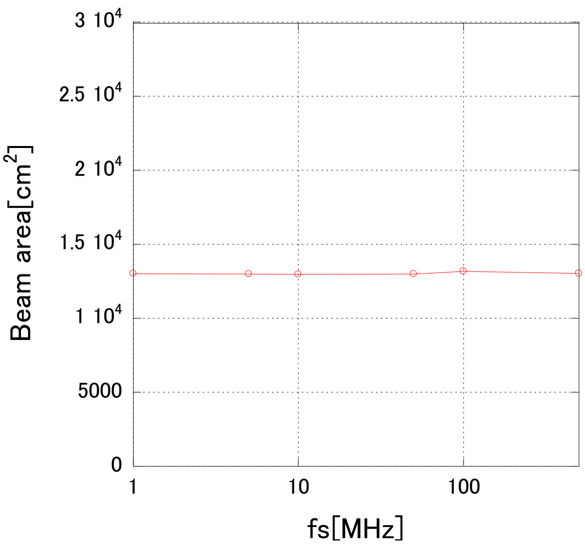


Figure 4.9 The variation of beam area in each frequency of signal wave f_s.

As shown in Fig.4.7 and 4.9, there would be no significant change in beam area when transmitted microwave beam isn't steered.

4.5.3 Discussion of beam area with transmitted beam steering using phased array

In this transmission system, phased array system is applied for microwave beam steered to circling target. In this case, phase of transmitted microwave is changing while steering. Thus, frequency is also changed. Therefore, beam area should be confirmed whether the beam area is changed or not using FM because frequency of modulated signal wave is changed. In this section, a result of variation of beam area with FM is mentioned.

Figure 4.10 shows position of steering microwave beam. In this calculation, beam area is estimated in each steering angle θ = 0, 45, 60, 90[deg.].

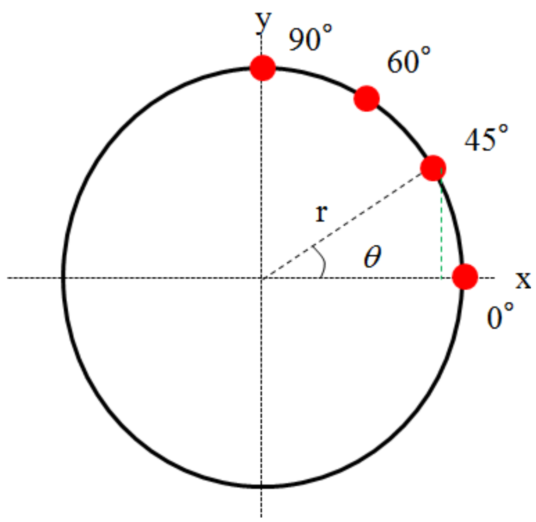


Figure 4.10 Position of steering microwave beam.

Figure 4.11 shows the variation of beam area in each value of θ without modulation. Then, Figure 4.12 shows the variation of beam area in each vale of θ with FM.

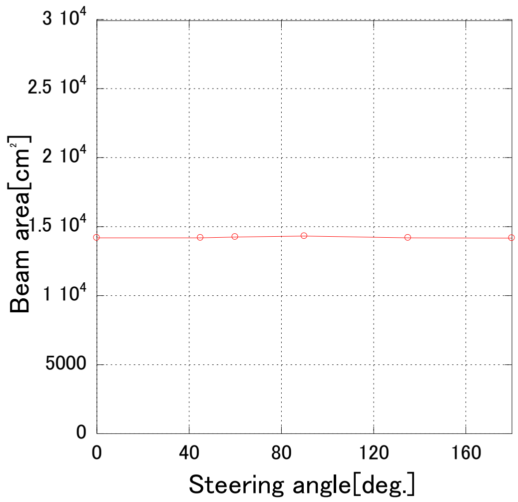


Figure 4.11 The variation of beam area in each value of θ without modulation.

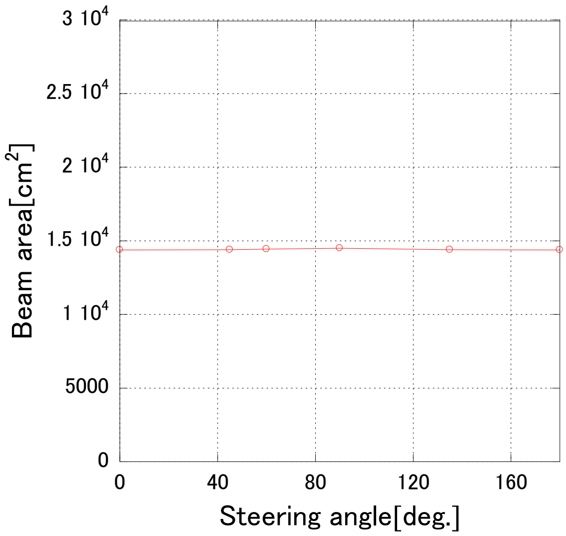


Figure 4.12 The variation of beam area in each vale of θ with FM.

As shown in Fig 4.11 and 4.12, there would be different in beam area while steering microwave beam.

Chapter 5 Conclusion

At tracking system, signal of wireless camera, which is 2.45GHz frequency modulated microwave, is used as a pilot signal and tracking for circling MAV while taking out picture information. The error was -3.22deg $\leqq \alpha_{rad} \leqq$ 2.22deg in radial-direction and was -2.42deg $\leqq \alpha_{azi} \leqq$ 4.97deg in azimuth-direction. By frequency modulation, phase shifting is occurred even if position of center is set accurately. Thus, with correcting this phase shift, experiment of tracking was done. However, circling motion of wireless camera can be detected. Thus, the position of MAV is almost detected and picture information from wireless camera can be received. In the result, tracking system which can get both position and picture information simultaneously is developed.

At transmitting system, numerical simulation of modulated microwave was done. In this simulation, three kinds of modulation is adopted transmitted microwave beam. Modulation pattern should be discussed which pattern is optimum for power transmitting system. Therefore, the efficiency of transmitting system using modulated microwave beam is estimated using numerical simulation by FDTD when transmitting beam is amplitude and frequency modulated. The beam area was discussed when transmitted beam is steered and not because this transmitting beam can be steered by phased array system.

In the result, there not would be significantly change of transmitted beam in each modulation method.

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