USRP based Narrowband Radar System for Doorway Detection

- MEng Qualifying Examination

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Outline

Literature Review and Motivations

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- **Unmanned Ground Vehicles (UGVs)** are mobile platforms that serve a wide range of specialized applications in urban, military, domestic, and industrial settings [1];

- A variety of **sensors** are utilized by UGVs to **autonomously** navigate in an unknown environment;

- **Vision system (Camera)** is applied for obstacle detection and environment mapping [2–4] while **laser sensor (Infrared)** is used for range detection [5,6].

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In these cases, **radar system** is expected to be robust to **autonomously** navigate the UGV.

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- Nonetheless, **UWB radar system** is quite expensive.
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Summary

In Short, in this MEng project we will focus on investigating and overcoming challenges that arise from using a low-cost narrowband USRP radar for UGVs indoor navigation.

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- to **design a narrowband radar** using the USRP software defined radio hardware platform and using MATLAB and C++ programming;
- to **carry out field measurements** to collect real radar signal data for detecting an open doorway in a realistic indoor environment;
- to **develop an effective algorithm** to process the collected data and guide an UGV to find the doorway and move through it.

Outline

Range Determination and Range Resolution

[1] Appendix A - Range Resolution

Range Determination and Range Resolution

Range Determination: **The distance** is determined by the time difference of the transmitting time and receiving time of the reflected electromagnetic waves, which is also called **round trip delay**. The range between the radar and the target is

$$R = \frac{c \cdot t}{2} \tag{1}$$

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Range Resolution[1]**:** **Range resolution** is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges [9], which is formulated as:

$$Range_{res} \geq \frac{c \cdot \tau}{2} \tag{2}$$

where τ is the pulse width time. **The equality** holds when all other factors except pulse width are at maximum efficiency.

[1] Appendix A - Range Resolution

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The radar range accuracy is upper bounded by the sampling rate in the receiver, which is calculate as:

$$Range_{acc} = \frac{c}{2 \cdot R_s} = \frac{c \cdot t_s}{2} \tag{3}$$

where R_s denotes sampling rate and t_s denotes sampling duration.

OFDM Radar Waveform

[2] Appendix B - Difference between Amplitude and Magnitude

OFDM Radar Waveform

Orthogonal Frequency-Division Multiplexing (OFDM) waveforms is implemented as radar waveform because **OFDM waveform** could be easily fused as **radar** and **communications** waveform.

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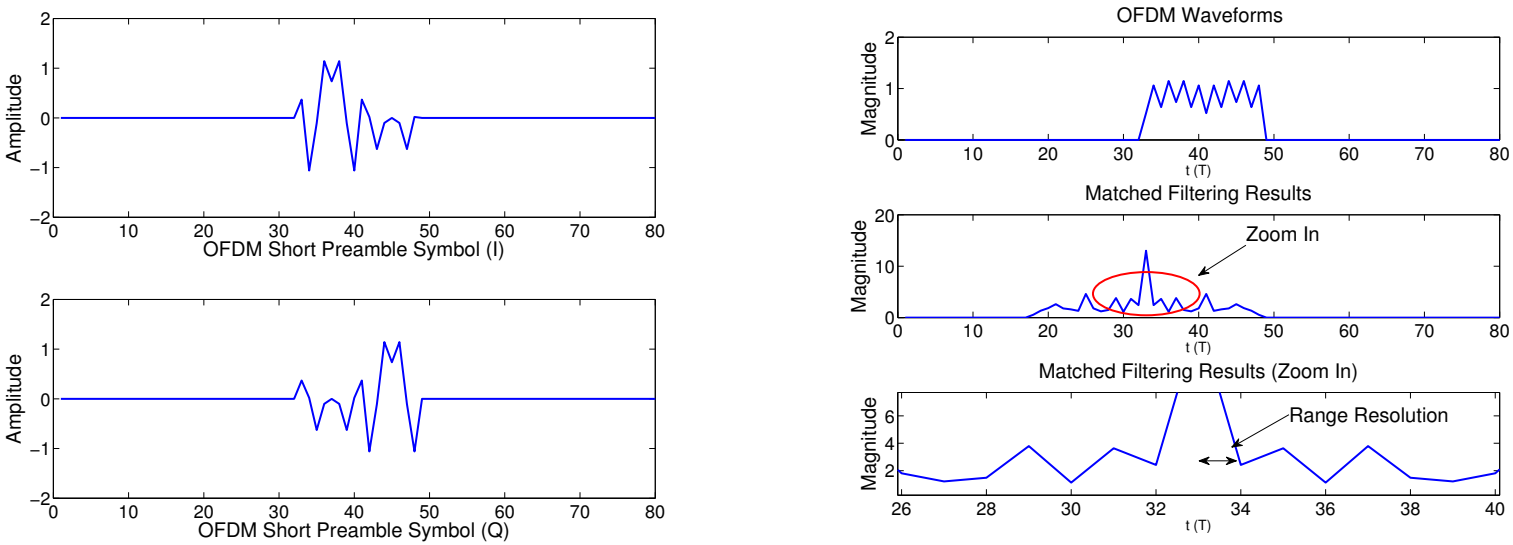


(a) OFDM Short Preamble Waveform (b) OFDM Waveform and Matched Filtering

Figure 1 : OFDM Radar Waveform and Matched Filtering Result[2]

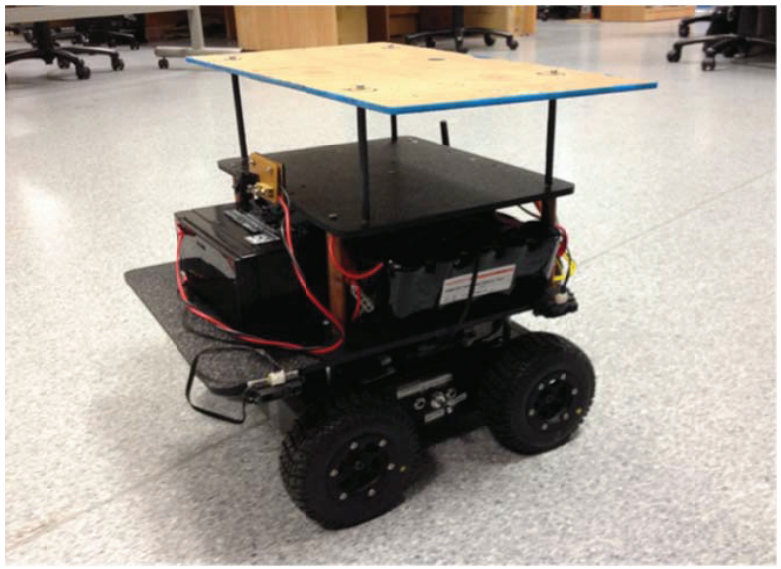
[2]Appendix B - Difference between Amplitude and Magnitude

USRP and UGV

USRP and UGV

- **The Universal Software Radio Peripheral (USRP)** products are computer-hosted software radios, where **GNU Radio** is the software to control this RF-end hardware;
- For USRP-based radar-guided UGV, **the Corobot Classic** [10] is used.

(a) USRP Network210 Series



(b) Corobot Classic

Figure 2 : USRP and UGV

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Figure 3 : Doorway Detection Environment

Open Doorway Detection Procedure

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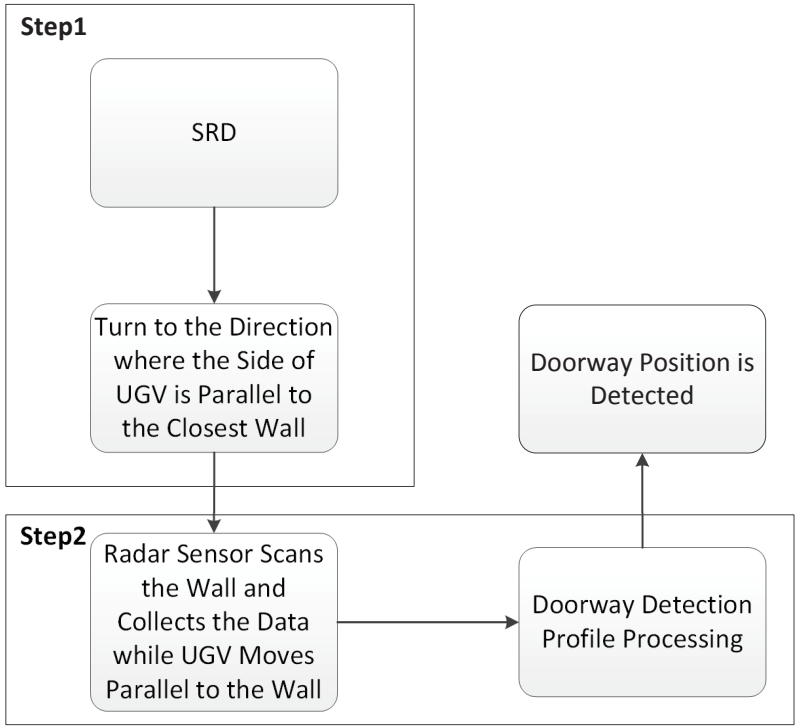

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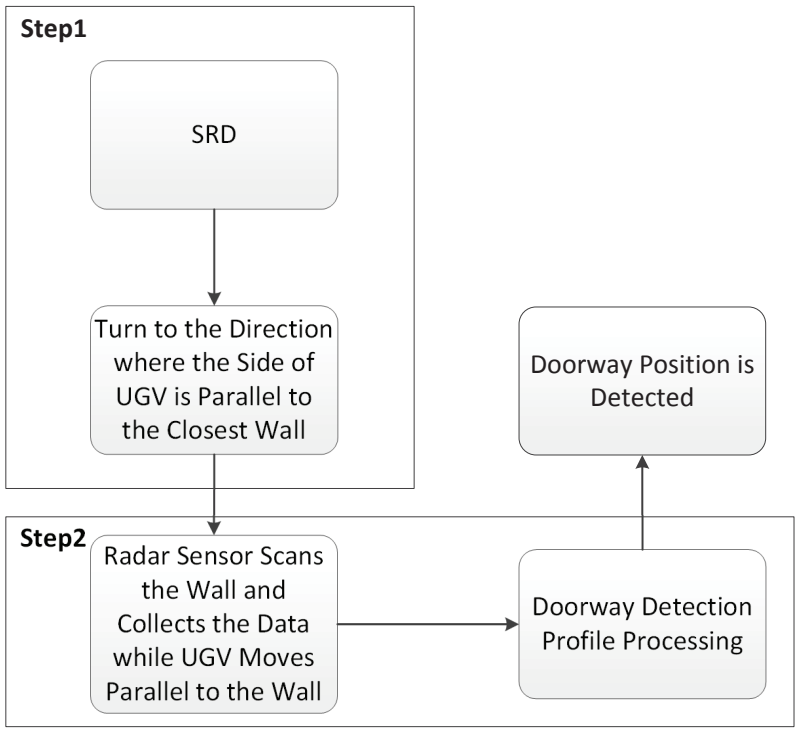

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Step1a: At the starting point, **Shortest Range Determination (SRD)** algorithm is applied to find the direction along which the robot is perpendicular to the nearest wall;

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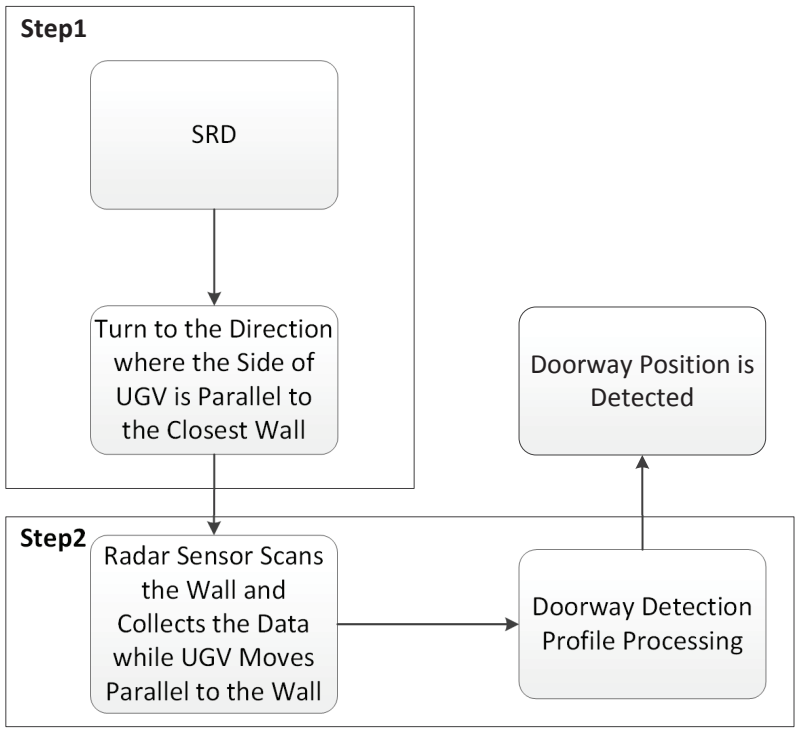

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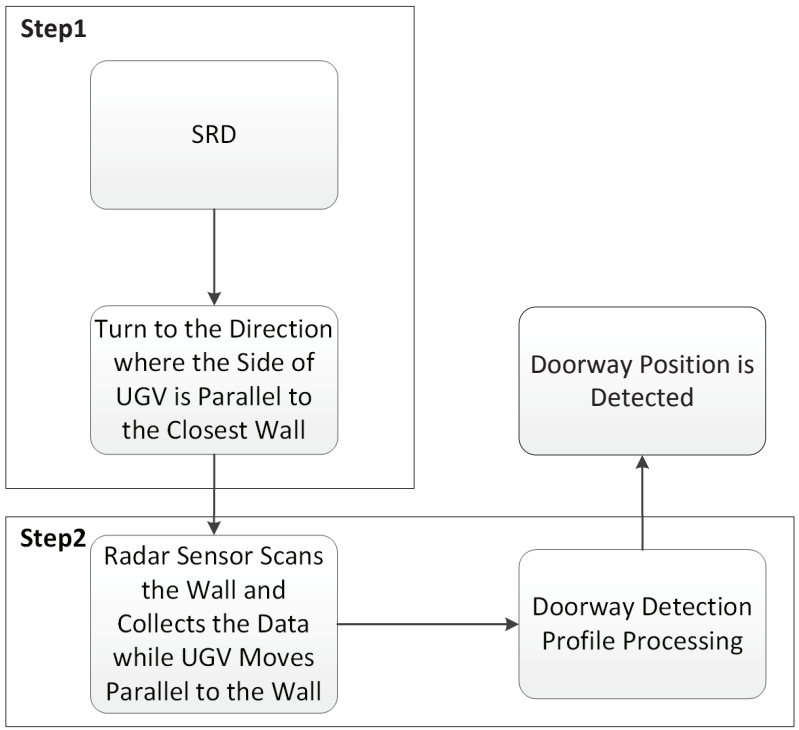

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Step2: The robot then moves along that direction **(parallel to the wall)** while the radar sensor scans the wall until the UGV meets another wall closely in front.

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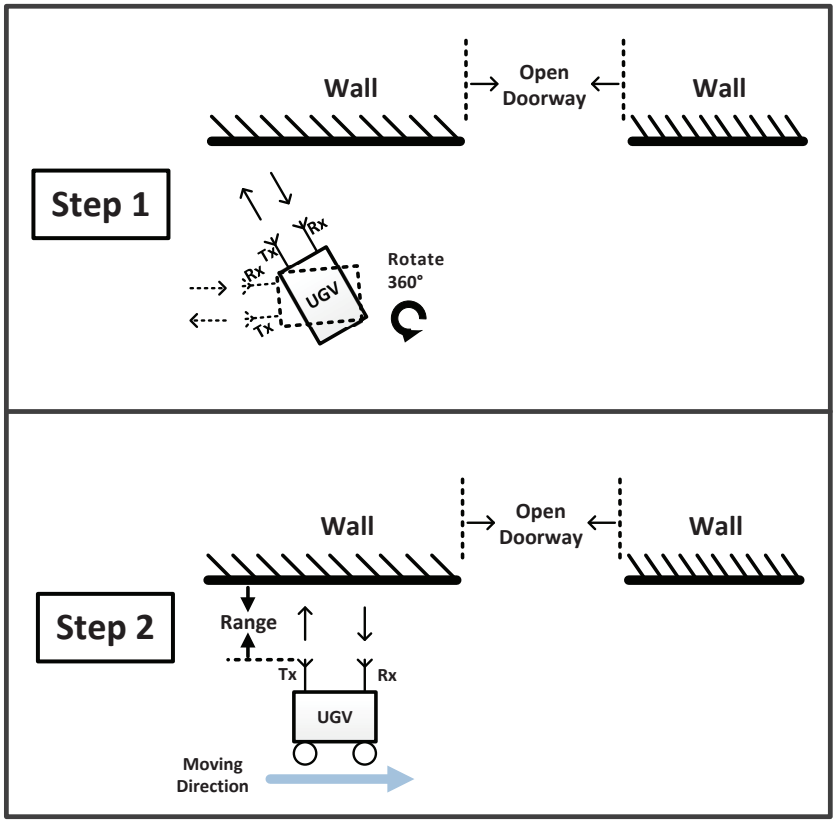

Figure 5 : Doorway Detection Procedure Illustration

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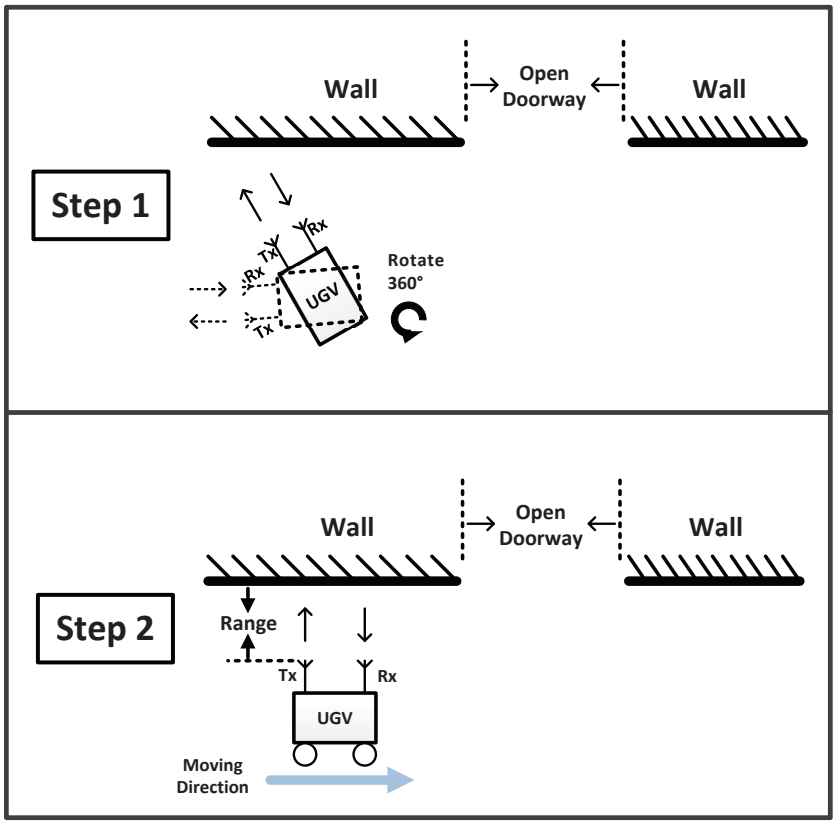

Figure 5 : Doorway Detection Procedure Illustration

- Two open doorway detection methods, namely **power-based doorway detection** and **ranging-based doorway detection**, are proposed.

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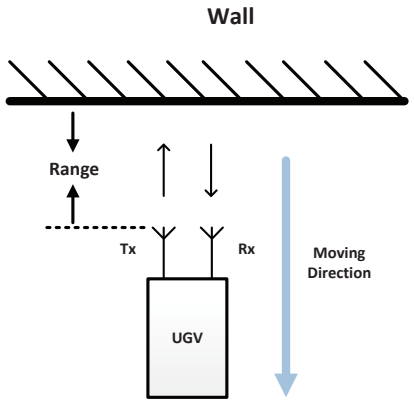
- Frames of OFDM symbols with **10MHz bandwidth** are transmitted **at 1.3GHz or 2GHz carrier frequency** and **the power** of received signal is calculated;
- In **"Step 1"**, **power-based SRD** is introduced;
- In **"Step 2"**, **power-based doorway detection method** is proposed and **corresponding doorway midpoint detection algorithm** is developed.

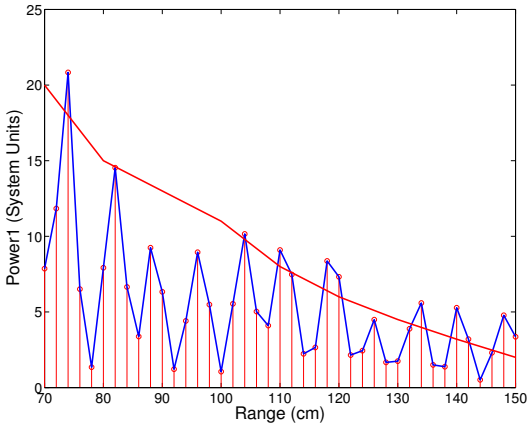
Fading Effect

[3]Appendix C - Radar Equation

Fading Effect



(a) Experiment Setup of "Fading vs Range" Measurement



(b) Experiment Results of "Fading vs Range" Measurement (2 GHz Carrier Frequency)

Figure 6 : Fading vs Range

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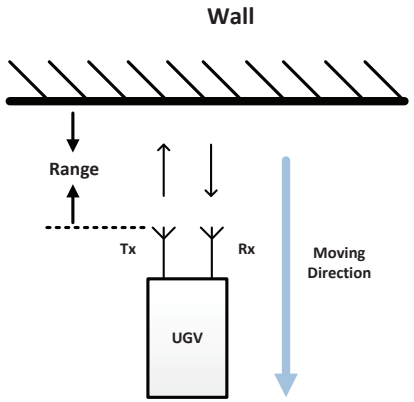

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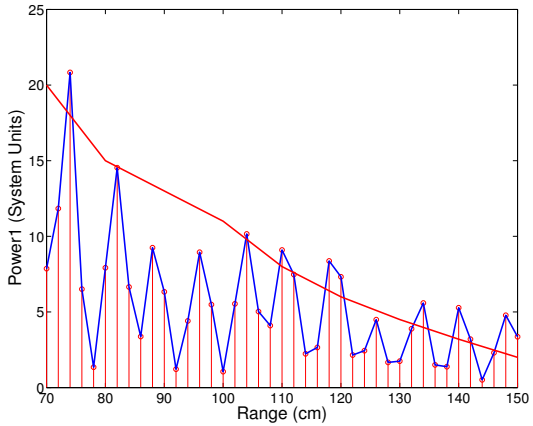

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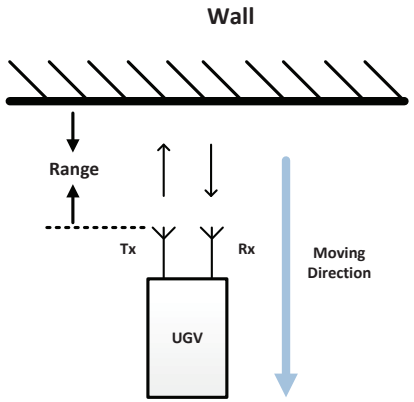

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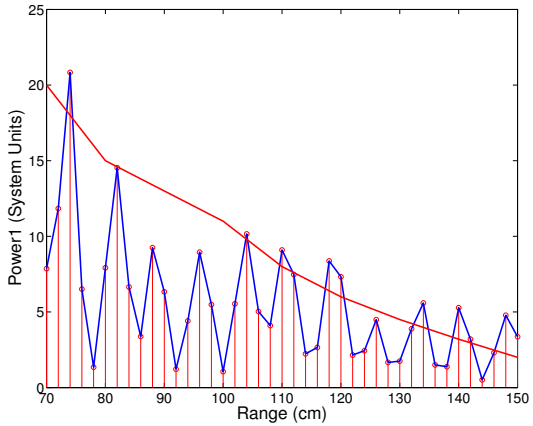

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- **Intuitively**, **the returned signal power** decreases **smoothly** while the UGV moves further away from the wall perpendicularly[3];
- **However**, **the returned signal power** changes dramatically with range **(Fading Effect)**, which **tremendously** affects the system;

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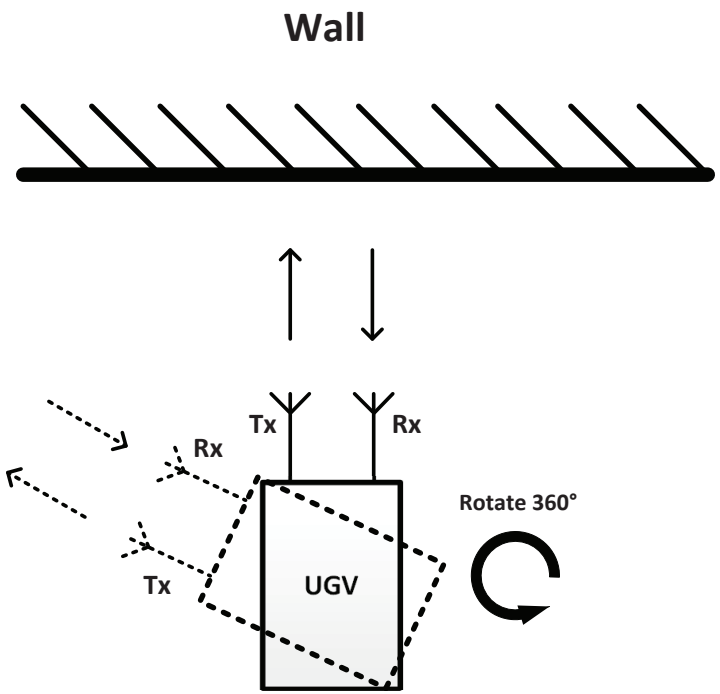

Figure 7 : Experimental Setup of Shortest Range Determination Measurement

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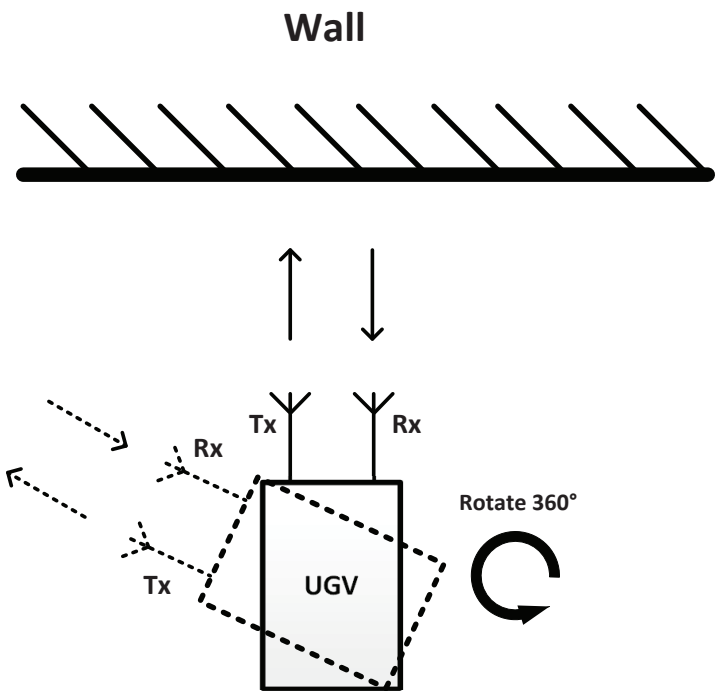

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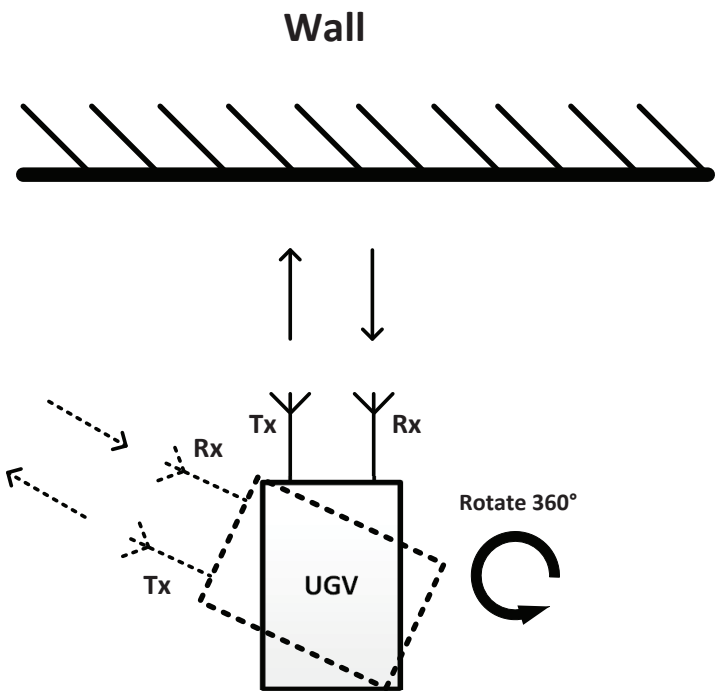

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- **However**, in the practical case, **the effect of fading and noise** are non-trivial.

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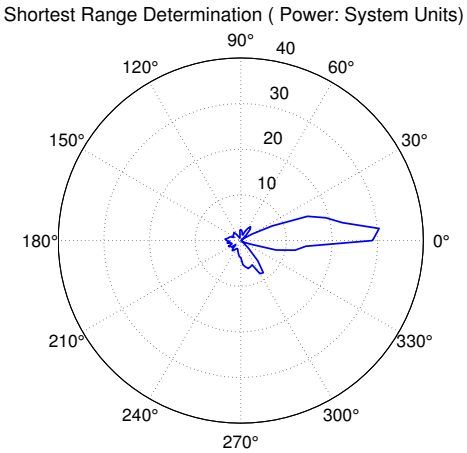
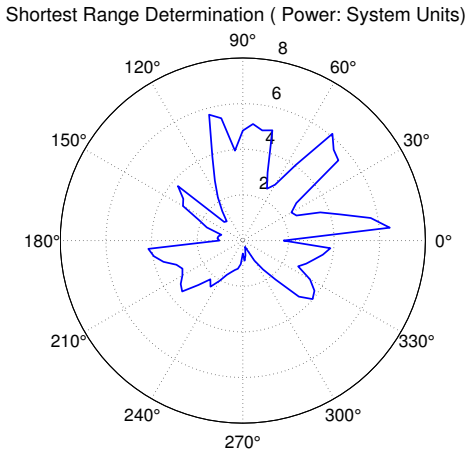


(a) Successful Example with 2GHz Carrier Frequency (Correct Nearest Wall Direction is at 0°)



(b) Unsuccessful Example with 1.3GHz Carrier Frequency (Correct Nearest Wall Direction is at 0°)

Figure 8 : Performance of SRD

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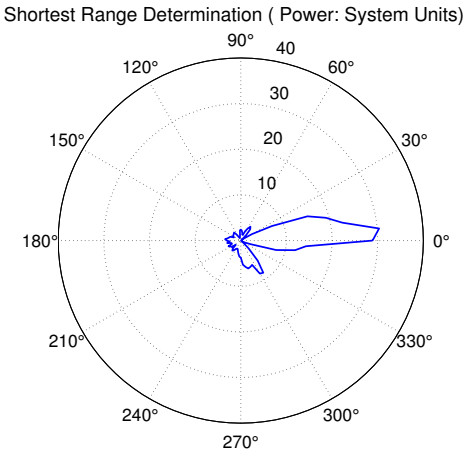

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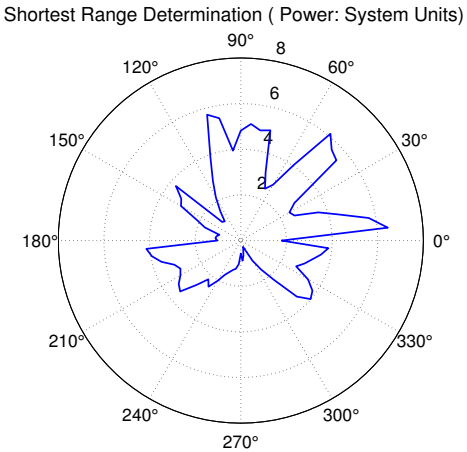

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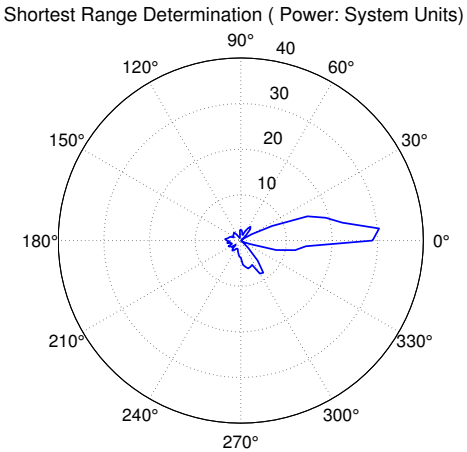

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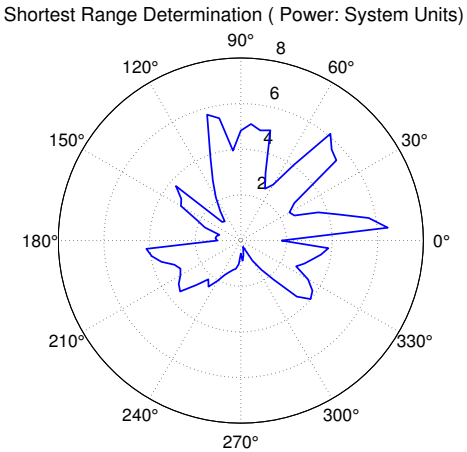

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- **Therefore**, **multi-frequencies SRD** should be applied.

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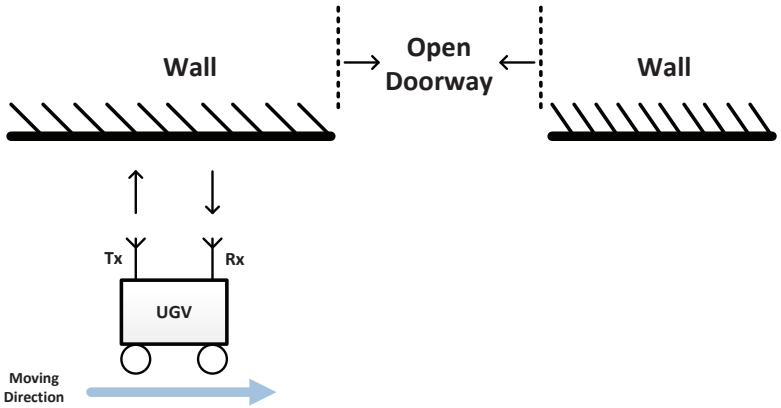

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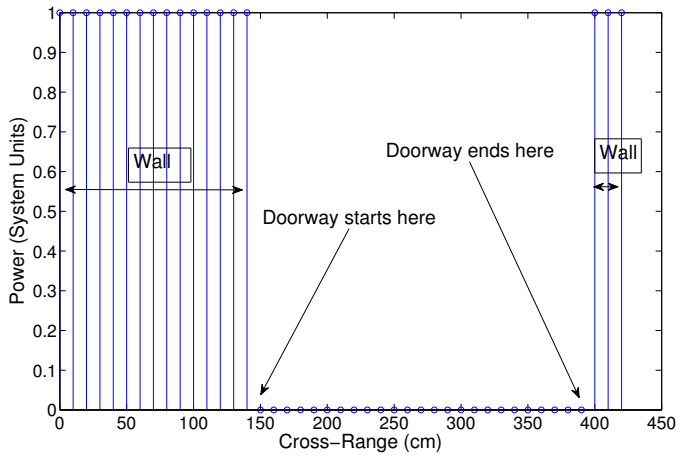

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Figure 9 : Ideal Power-based Doorway Detection

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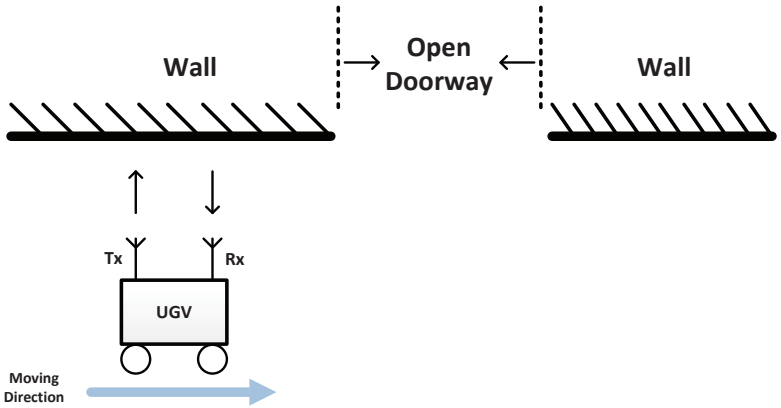

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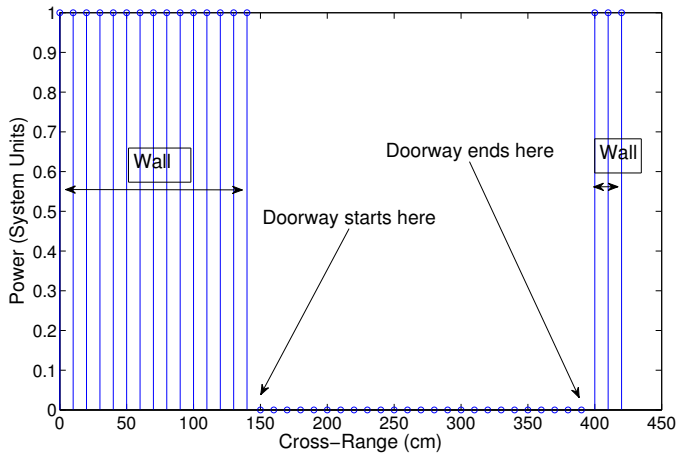

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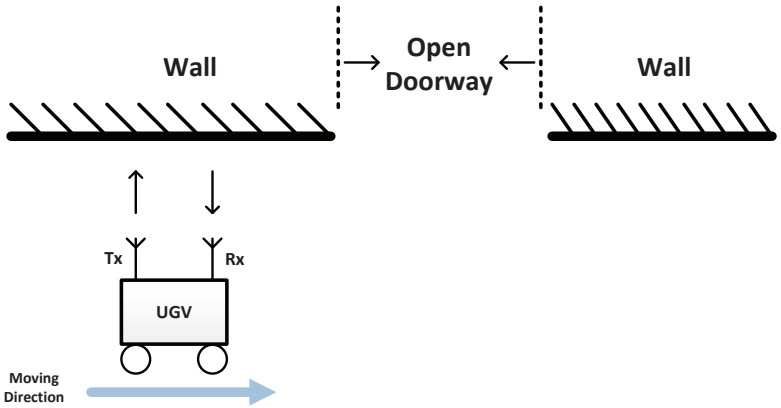

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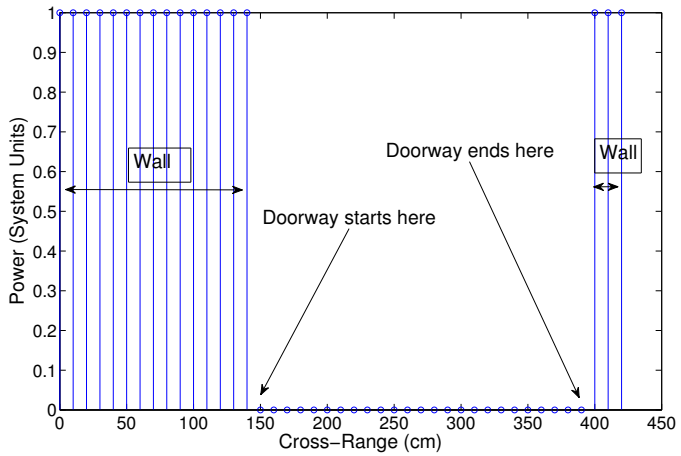


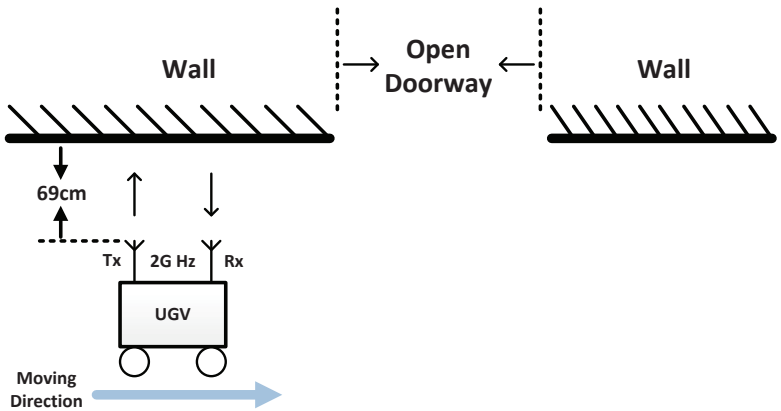
(b) Ideal Detection Profile

Figure 9 : Ideal Power-based Doorway Detection

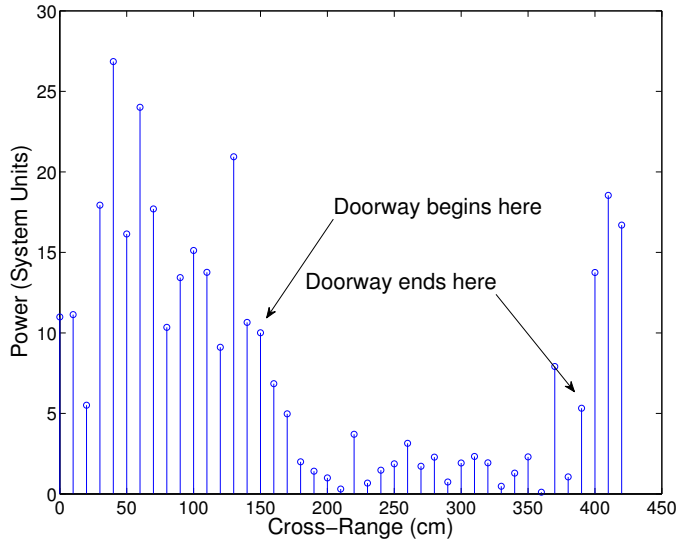
- The radar will move in a direction that is **parallel to the wall**;
- **The returned signal power** will be expected to remain roughly constant **until** the UGV is positioned to face the open doorway directly;
- Then **the returned signal power** will be expected to be **zero**.

"Step 2" Measurements - Practical Case

"Step 2" Measurements - Practical Case



(a) Experimental Setup of Detection Measurement at 69cm with 2GHz Carrier Frequency



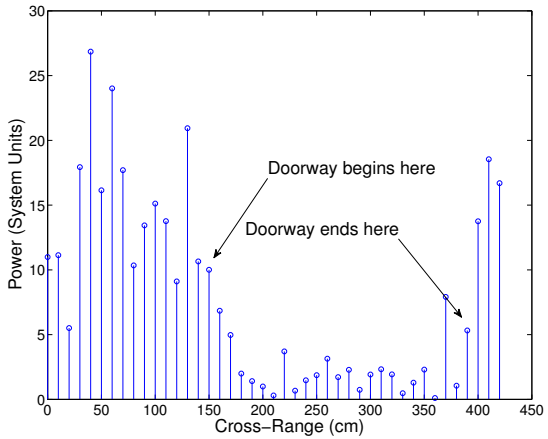
(b) Example of Good Detection Profile at 69cm with 2GHz Carrier Frequency

Figure 10 : Practical Power-based Doorway Detection

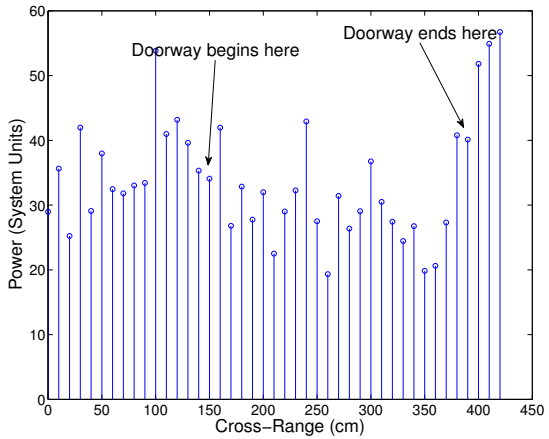
- **However**, in practical measurements, **multipath reflection** are found to introduce random power fluctuations to **the returned signal powers**.

"Step 2" Measurements - Practical Case

"Step 2" Measurements - Practical Case



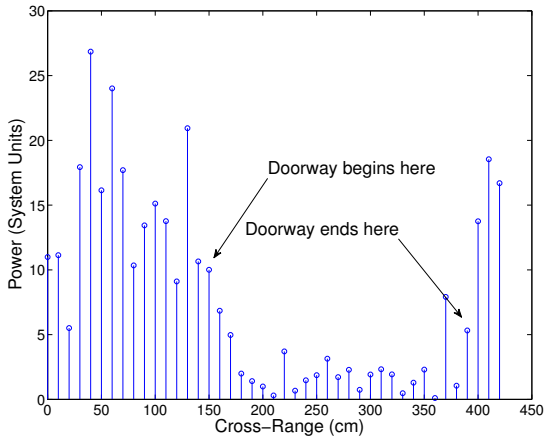
(a) Example of Good Detection Profile at 69cm with 2 GHz Carrier Frequency



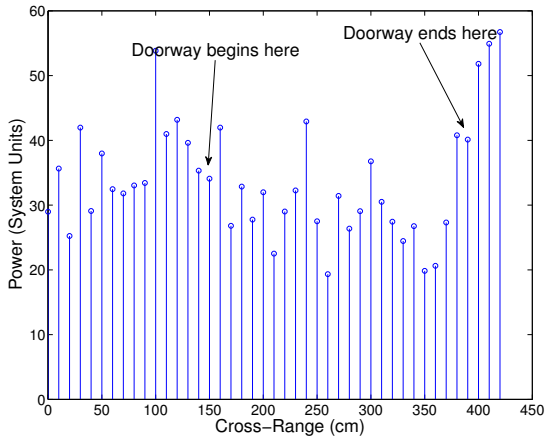
(b) Example of Bad Detection Profile at 69cm with 1.3 GHz Carrier Frequency

Figure 11 : Comparison of Power-based Doorway Detection Profile

"Step 2" Measurements - Practical Case



(a) Example of Good Detection Profile at 69cm with 2 GHz Carrier Frequency

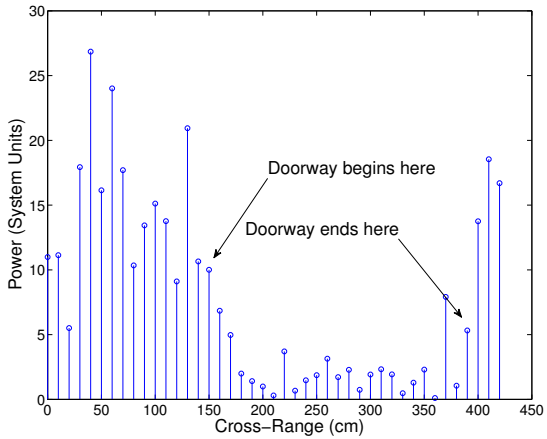


(b) Example of Bad Detection Profile at 69cm with 1.3 GHz Carrier Frequency

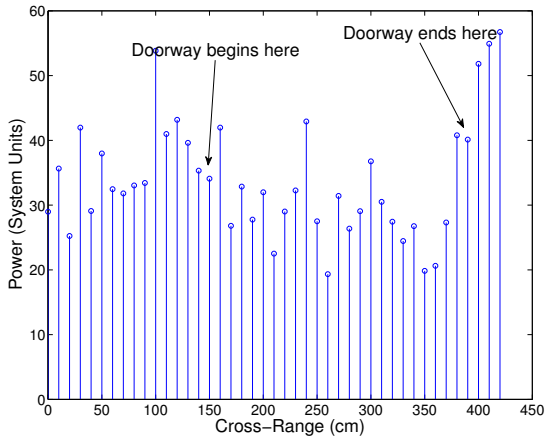
Figure 11 : Comparison of Power-based Doorway Detection Profile

- At 69 cm, it is clear that detection profile at **2 GHz** carrier outperforms the one at **1.3 GHz** due to the reason that the power readings at **1.3 GHz** are severely corrupted by the fading effects;

"Step 2" Measurements - Practical Case



(a) Example of Good Detection Profile at 69cm with 2 GHz Carrier Frequency



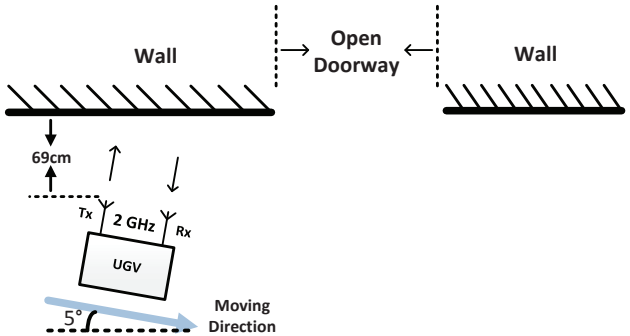
(b) Example of Bad Detection Profile at 69cm with 1.3 GHz Carrier Frequency

Figure 11 : Comparison of Power-based Doorway Detection Profile

- At 69 cm, it is clear that detection profile at **2 GHz** carrier outperforms the one at **1.3 GHz** due to the reason that the power readings at **1.3 GHz** are severely corrupted by the fading effects;
- **Therefore**, **multi-frequencies doorway detection** should be applied.

"Step 2" Measurements with SRD Error

"Step 2" Measurements with SRD Error



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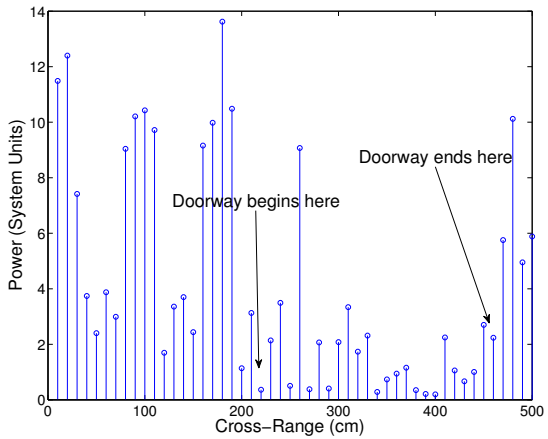
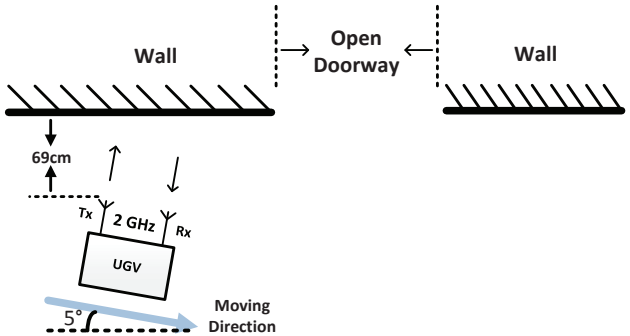


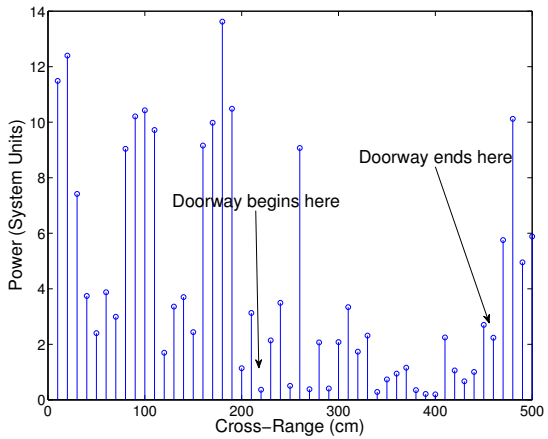
(b) Detection Profile with 5° SRD Error

Figure 12 : Power-based Doorway Detection Profile at 2 GHz with 5° SRD Error

"Step 2" Measurements with SRD Error



(a) Experimental Setup of Detection Measurement



(b) Detection Profile with 5° SRD Error

Figure 12 : Power-based Doorway Detection Profile at 2 GHz with 5° SRD Error

- **Besides fading effect**, **SRD** may also have errors due to the finite step size in angular rotation;
- In Fig. 12(b), **the returned signal power** show some additional variations due to the fading effect.

Doorway Midpoint Detection Algorithm

Doorway Midpoint Detection Algorithm

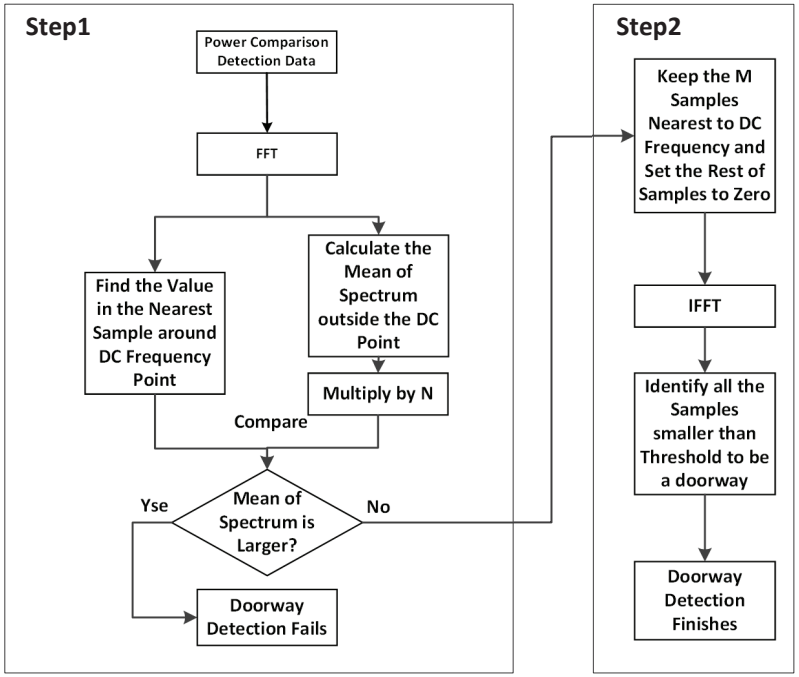


Figure 13 : Doorway Midpoint Detection Algorithm Block Diagram - **Frequency Domain Filtering Algorithm**

- **The objective** is to guide the UGV to find a doorway and go through it. Therefore, **doorway midpoint detection** is a reasonable choice.

Doorway Midpoint Detection Algorithm

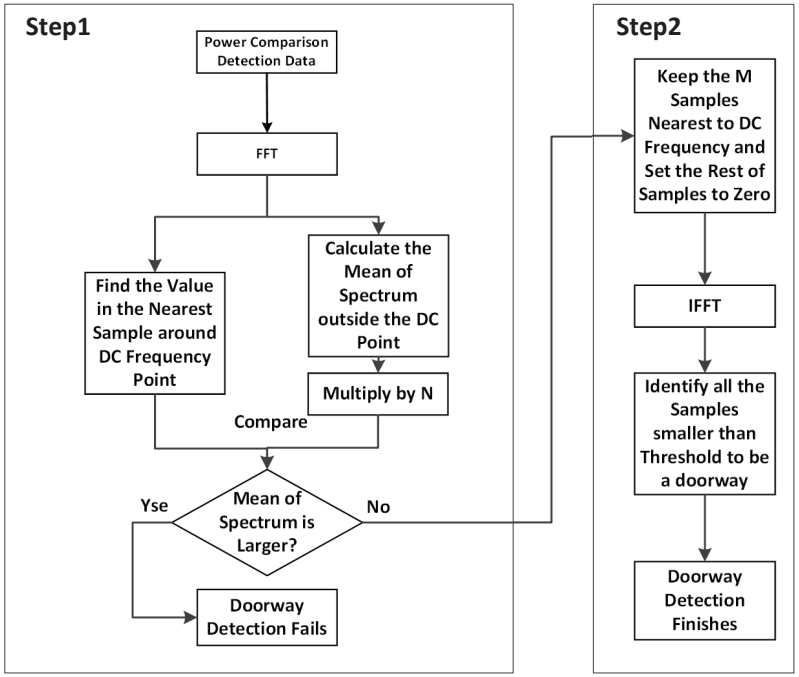
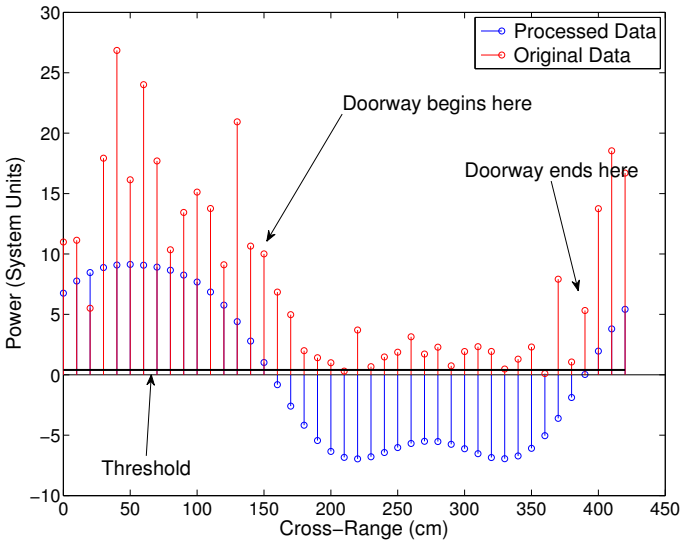


Figure 13 : Doorway Midpoint Detection Algorithm Block Diagram - **Frequency Domain Filtering Algorithm**

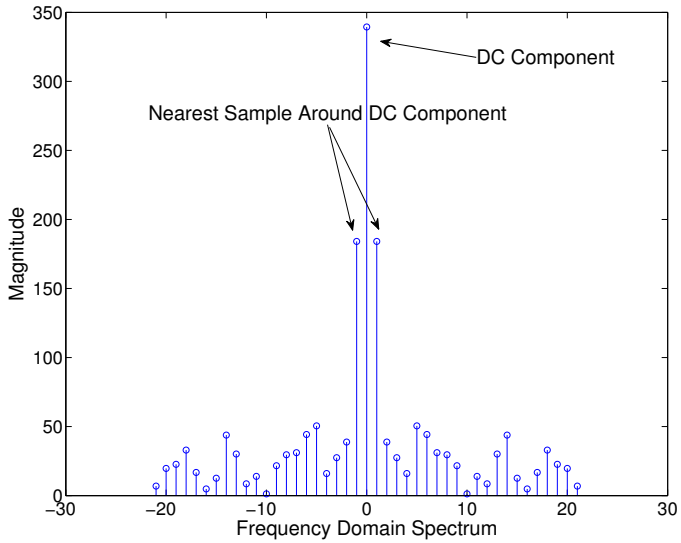
- **The objective** is to guide the UGV to find a doorway and go through it. Therefore, **doorway midpoint detection** is a reasonable choice.
- **Higher frequency components** of the returned signal power profile contain **the irrelevant information** of the doorway position.

Doorway Midpoint Detection Algorithm

Doorway Midpoint Detection Algorithm



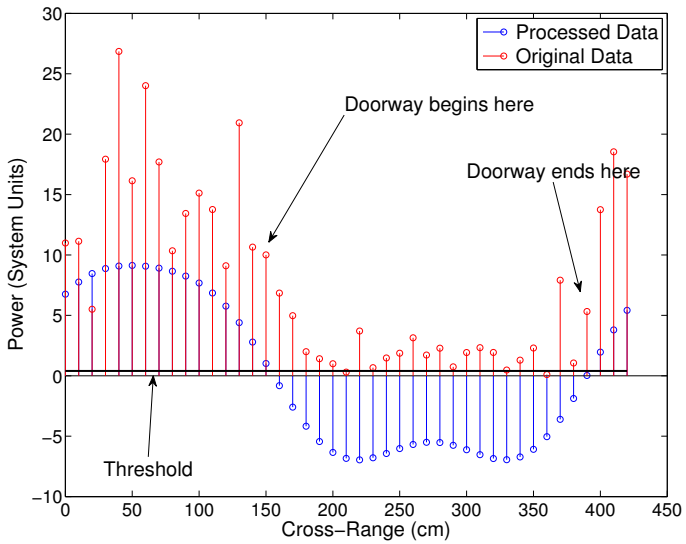
(a) Detection Profile and Processed Results at 69cm with 2 GHz Carrier Frequency



(b) Frequency Spectrum of Detection Profile at 69cm with 2 GHz Carrier Frequency

Figure 14 : Power-based Doorway Detection Algorithm Illustration

Doorway Midpoint Detection Algorithm



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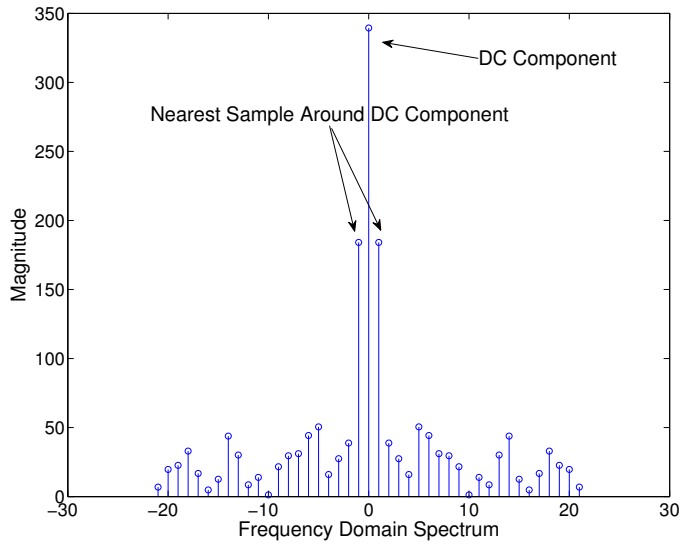


(b) Frequency Spectrum of Detection Profile at 69cm with 2 GHz Carrier Frequency

Figure 14 : Power-based Doorway Detection Algorithm Illustration

- **The best threshold** is chosen by minimizing the errors of detecting the doorway midpoint of all the experiment results;
- We set $N = 4, M = 3$ and threshold is 0.4 based on our experience.

Doorway Midpoint Detection Results

Doorway Midpoint Detection Results

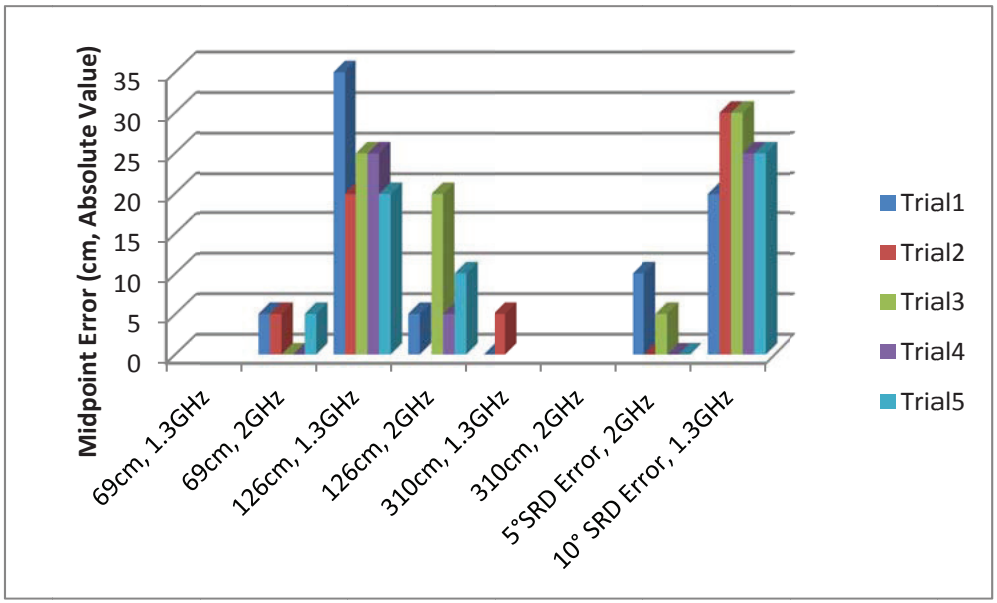


Figure 15 : Power-based Doorway Midpoint Detection Errors obtained from Experiment Data

Doorway Midpoint Detection Results

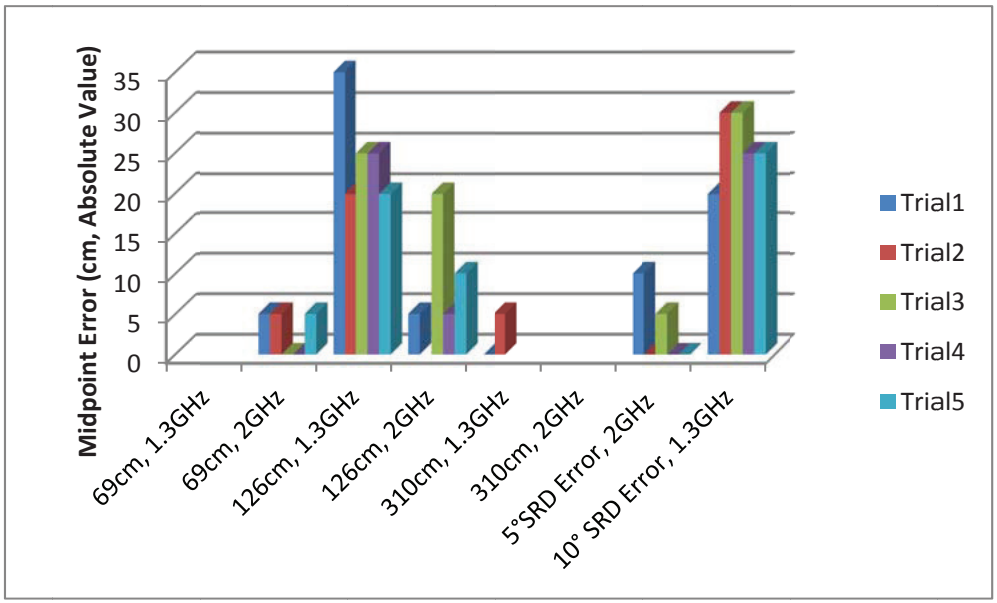
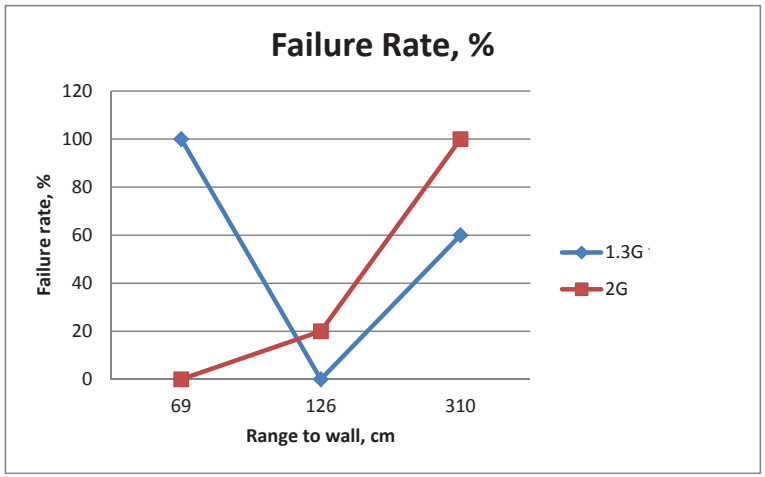


Figure 15 : Power-based Doorway Midpoint Detection Errors obtained from Experiment Data

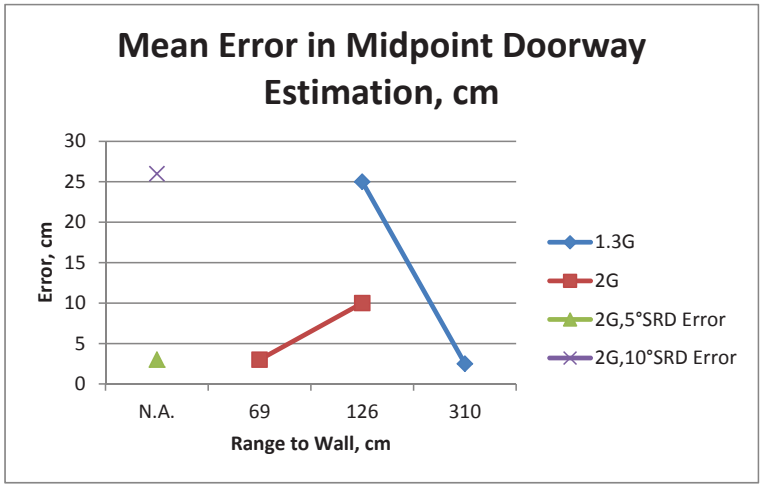
- There are 40 trials of experiment data collected for **power-based doorway detection method**;
- **The blank parts** shown in the histogram indicate the detection failure;
- **True doorway length** is 240 centimeters.

Doorway Midpoint Detection Results

Doorway Midpoint Detection Results



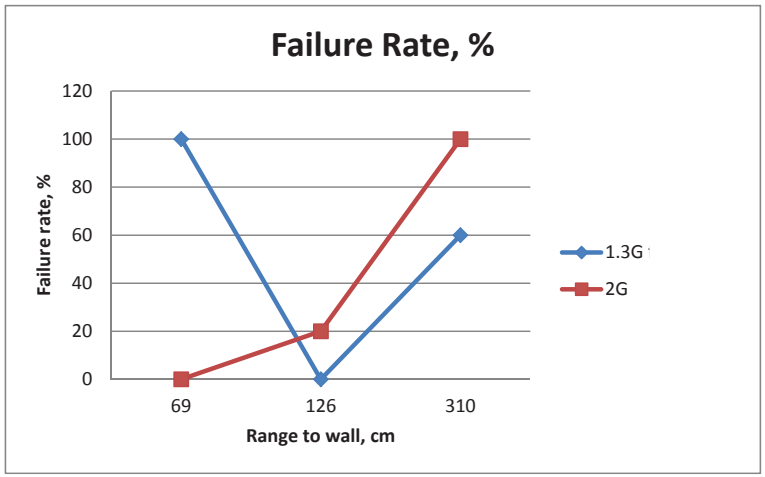
(a) Failure Rate



(b) Mean Error

Figure 16 : Doorway Midpoint Estimation of Power-based Doorway Detection Algorithm

Doorway Midpoint Detection Results



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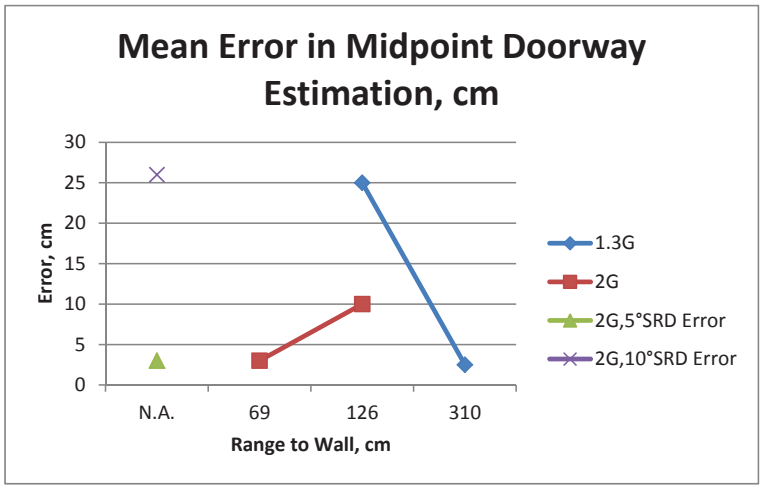
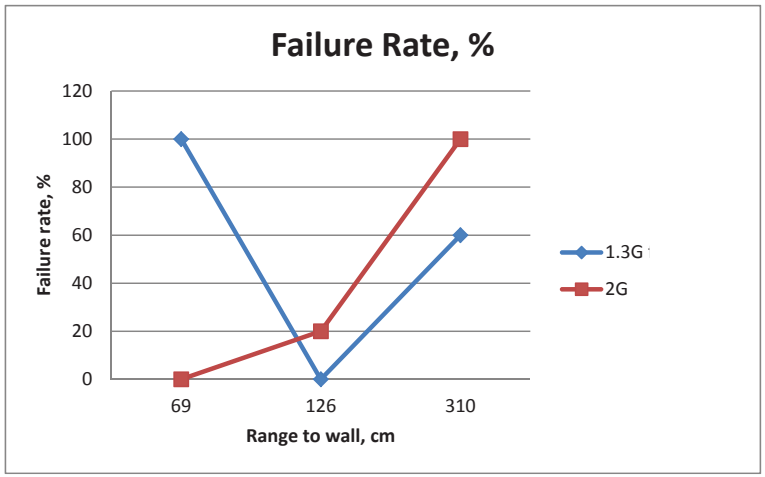


(b) Mean Error

Figure 16 : Doorway Midpoint Estimation of Power-based Doorway Detection Algorithm

- **The high failure rate** at Range 310cm is caused by low SNR, i.e. high noise;

Doorway Midpoint Detection Results



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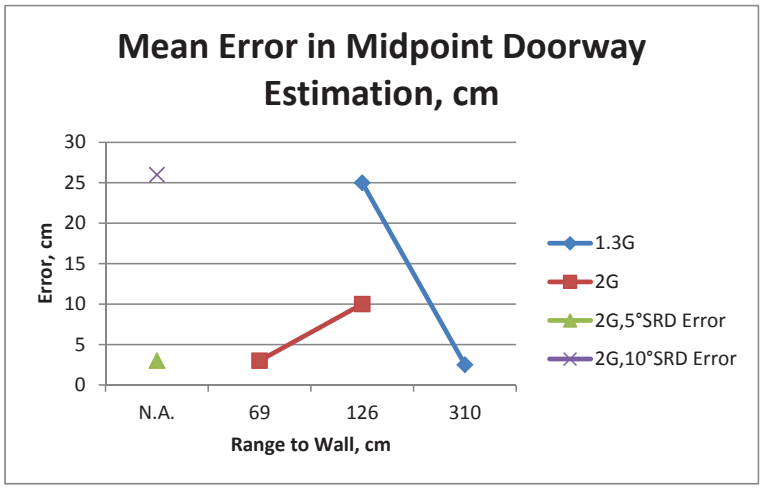

(b) Mean Error

Figure 16 : Doorway Midpoint Estimation of Power-based Doorway Detection Algorithm

- **The high failure rate** at Range 310cm is caused by low SNR, i.e. high noise;
- **The high failure rate** at Range 69cm with 1.3GHz Carrier Frequency is due to **the fading effect**.

Introduction to Ranging-based Doorway Detection

Introduction to Ranging-based Doorway Detection

- We propose an alternative doorway detection method by **using range**, instead of **the returned signal power**;

Introduction to Ranging-based Doorway Detection

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- **The basic principle** is that a short range will be detected by radar if it faces a wall, and range will be not applicable (the reflected signal is too weak) if it faces an open doorway.

Introduction to Ranging-based Doorway Detection

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- **"Step 1"** measurements is skipped because the ranging-based SRD is extremely unstable. **Hence** we decide to utilize the same approach, **power-based SRD** to finish the SRD method.

Introduction to Ranging-based Doorway Detection

- We propose an alternative doorway detection method by **using range**, instead of **the returned signal power**;
- **The basic principle** is that a short range will be detected by radar if it faces a wall, and range will be not applicable (the reflected signal is too weak) if it faces an open doorway.
- **"Step 1"** measurements is skipped because the ranging-based SRD is extremely unstable. **Hence** we decide to utilize the same approach, **power-based SRD** to finish the SRD method.
- In **"Step 2"**, **ranging-based doorway detection method** is proposed and **corresponding doorway midpoint detection algorithm** is developed.

Introduction to Ranging-based Doorway Detection

[4] Appendix D - Interpolation

Introduction to Ranging-based Doorway Detection

- Frames of OFDM symbols with **10 MHz bandwidth** at 2 GHz carrier frequency are transmitted;

[4] Appendix D - Interpolation

Introduction to Ranging-based Doorway Detection

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- The received signals are oversampled at **a symbol rate of 25 MHz** so **the range accuracy** is 6 meters according to (4);

[4] Appendix D - Interpolation

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[4] Appendix D - Interpolation

Introduction to Ranging-based Doorway Detection

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[4] Appendix D - Interpolation

Introduction to Ranging-based Doorway Detection

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- The received signals are oversampled at **a symbol rate of 25 MHz** so **the range accuracy** is 6 meters according to (4);
- **Matched filtering** is then used to obtain the correlated signals;
- In order to estimate the peak point more accurate, the correlated signals are interpolated by **a interpolation factor of 4** and position of peak point is found to indicate the beginning of received signals[4];
- Therefore, in this case, **one symbol duration indicates a range of 150cm**, i.e. **the estimation accuracy** is 150cm, where the range value in our detection result is chosen from $\{0cm, 150cm, 300cm, 450cm, ...\}$

[4] Appendix D - Interpolation

"Step 2" Measurements - Ideal Case

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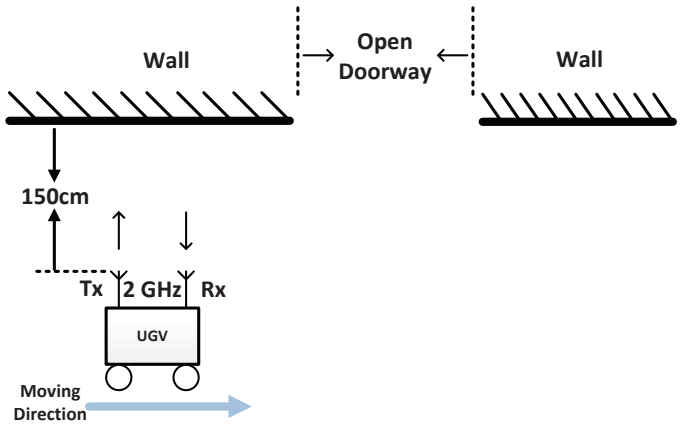
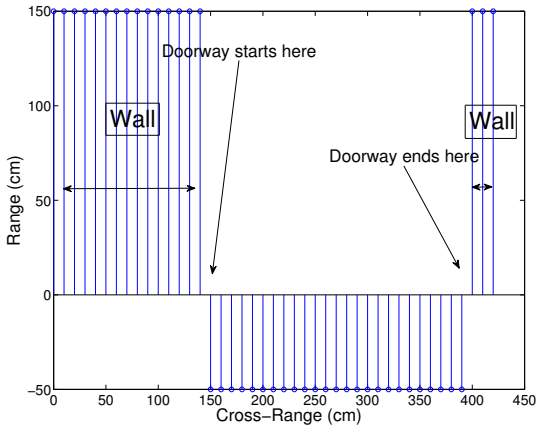


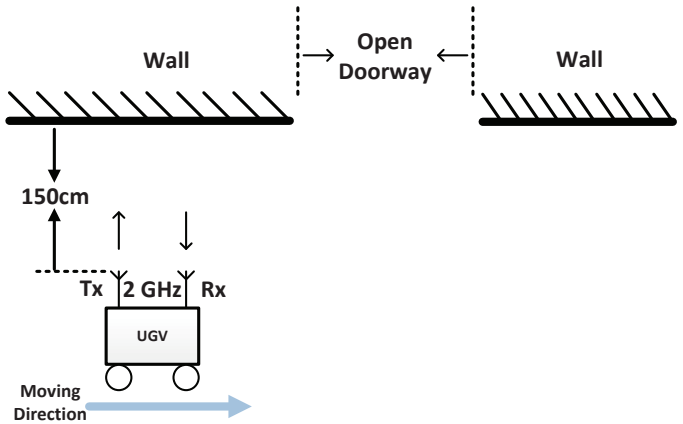
(a) Experimental Setup of Detection Measurement



(b) Ideal Detection Profile (True Distance to the Wall is 150cm)

Figure 17 : Ideal Ranging-based Doorway Detection

"Step 2" Measurements - Ideal Case



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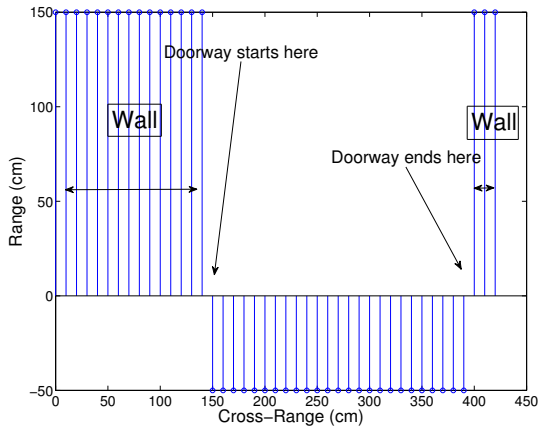

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- In the ideal case, **the ranging values** are expected to remain in **a constant range** (the actual distance between the wall and the antenna) while the antenna is **facing the wall**;

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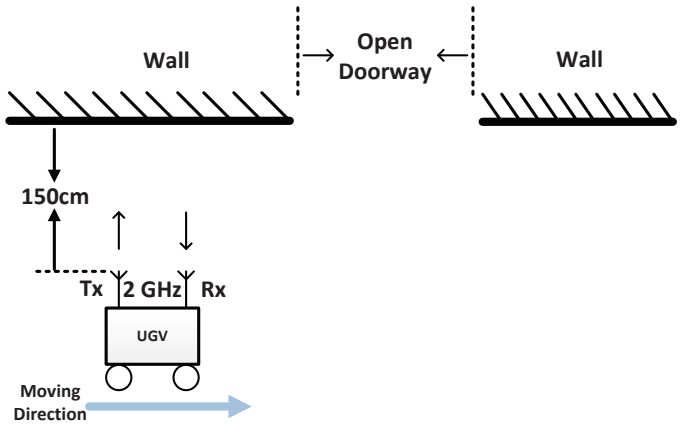

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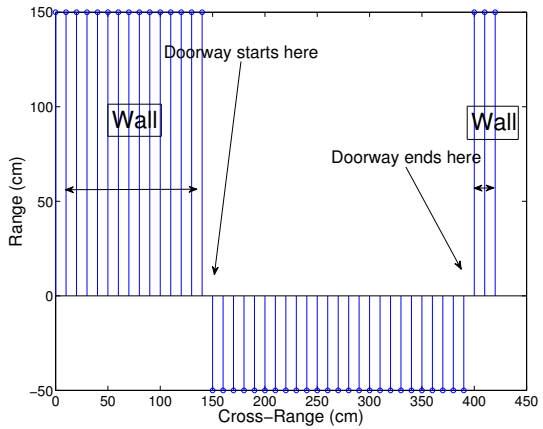

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Figure 17 : Ideal Ranging-based Doorway Detection

- In the ideal case, **the ranging values** are expected to remain in **a constant range** (the actual distance between the wall and the antenna) while the antenna is **facing the wall**;
- Once the UGV is positioned directly **in front of the doorway**, **the ranging values** should be **not applicable** (We use -50cm to be the synonym of the phrase "Not Applicable").

"Step 2" Measurements - Practical Case - Facing the Open Doorway

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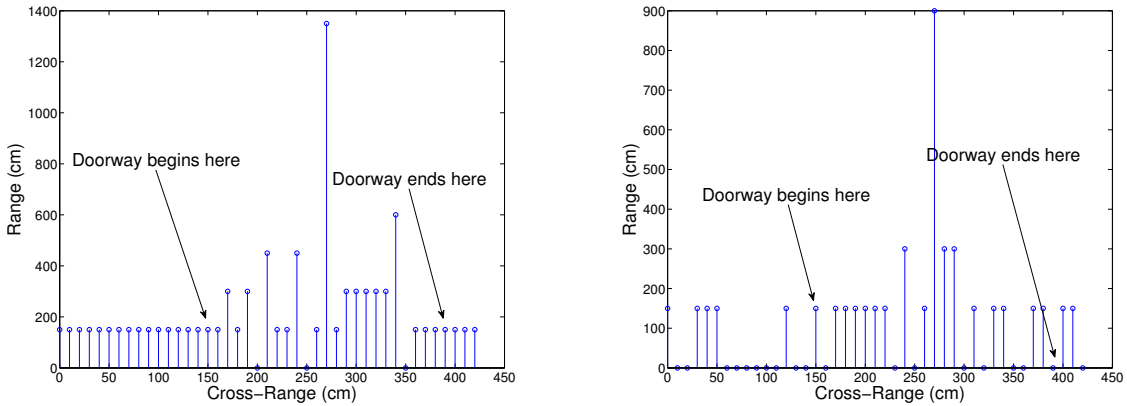


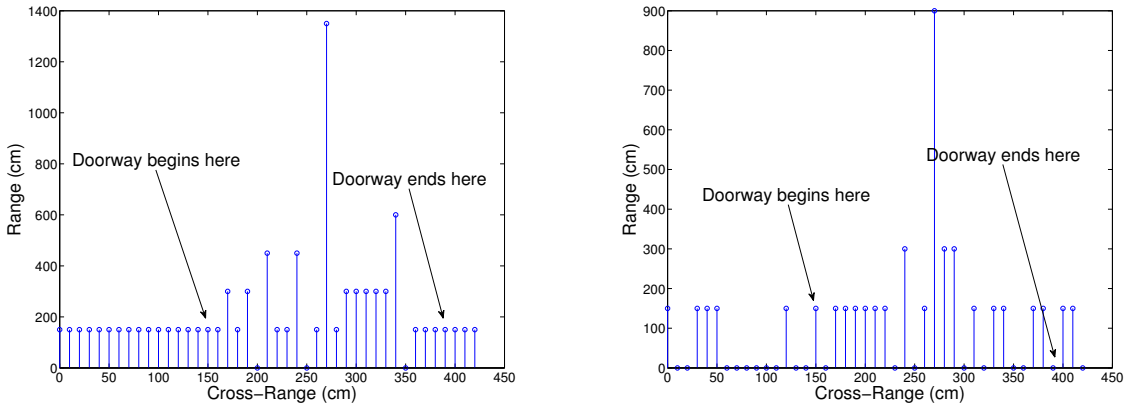
(a) Detection Profile at 126 cm with 2 GHz Carrier Frequency

(b) Detection Profile at 69 cm with 2 GHz Carrier Frequency

Figure 18 : Practical Ranging-based Doorway Detection

- **However**, in the practical case, **the fluctuation** in range values is due to the complicated indoor environment;

"Step 2" Measurements - Practical Case - Facing the Open Doorway



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- **However**, in the practical case, **the fluctuation** in range values is due to the complicated indoor environment;
- Sometimes the reflected path directly transmitted from the transmit antenna may **dominate** the received power;
- Besides, the power of the reflected signal from the ceiling or floor may be **dominant**.

"Step 2" Measurements - Practical Case - Facing the Wall

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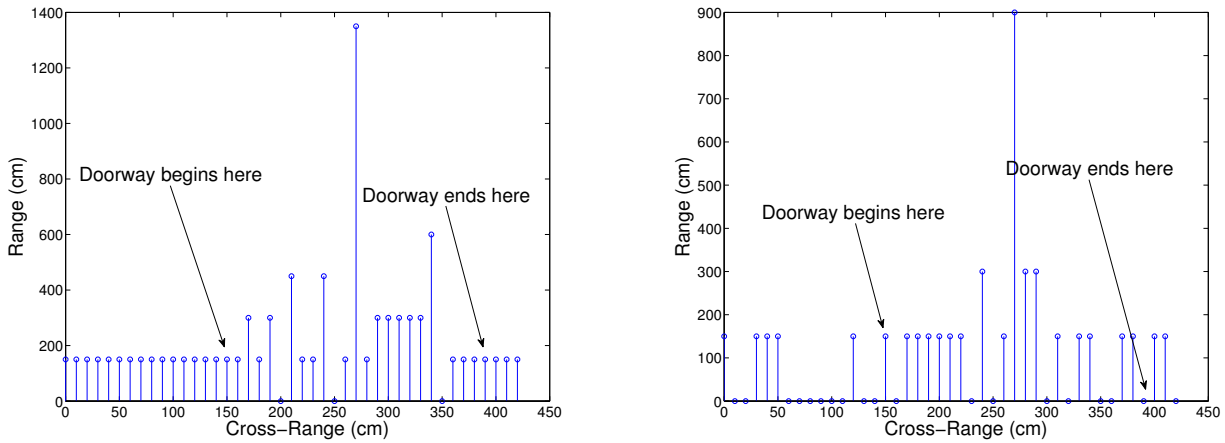

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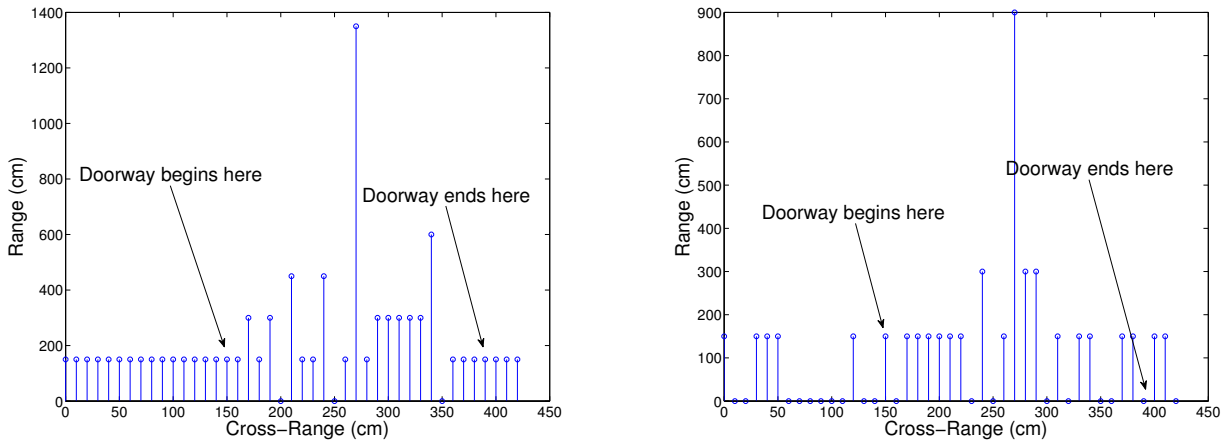

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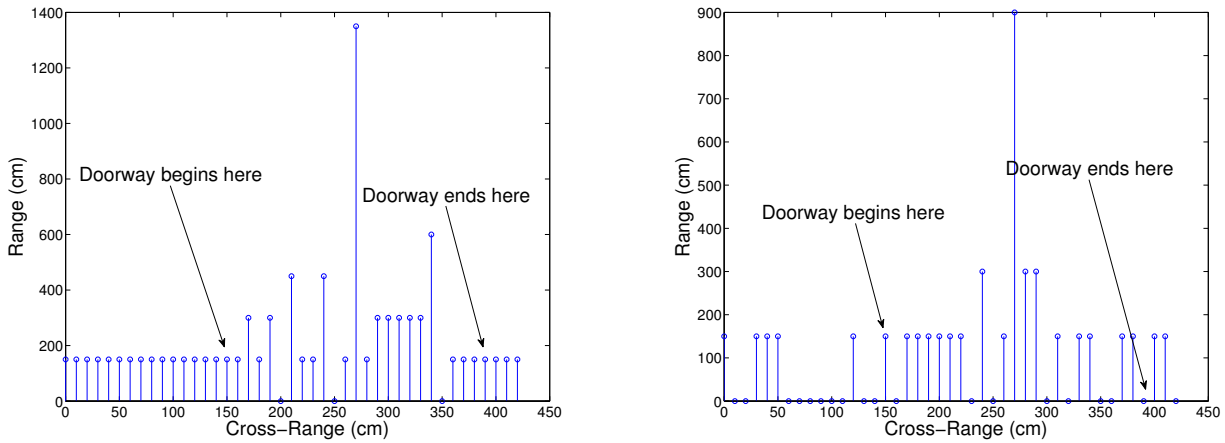
Figure 19 : Practical Ranging-based Doorway Detection

- For the ranging-based doorway detection profile **at 126cm**, the range values are very stable to **150 cm**;

"Step 2" Measurements - Practical Case - Facing the Wall



(a) Detection Profile at 126 cm with 2 GHz Carrier Frequency

(b) Detection Profile at 69 cm with 2 GHz Carrier Frequency

Figure 19 : Practical Ranging-based Doorway Detection

- For the ranging-based doorway detection profile **at 126cm**, the range values are very stable to **150 cm**;
- For the ranging-based doorway detection profile **at 69 cm**, the range value oscillates **between 0 cm and 150 cm**.

"Step 2" Measurements - Practical Case - Ambiguous Range

"Step 2" Measurements - Practical Case - Ambiguous Range

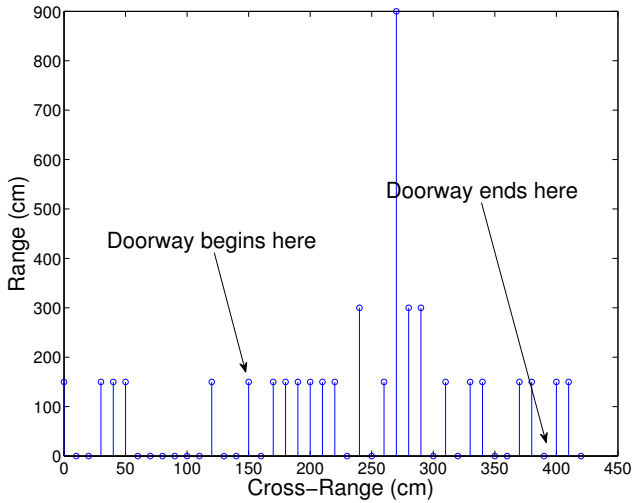


Figure 20 : Power-based Doorway Midpoint Detection Errors obtained from Experiment Data

"Step 2" Measurements - Practical Case - Ambiguous Range

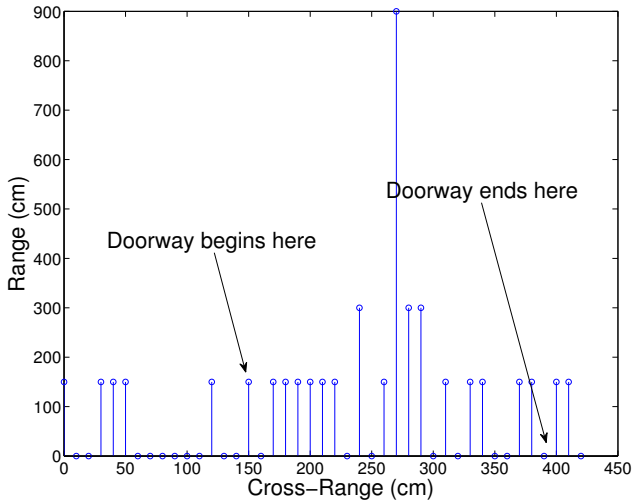


Figure 20 : Power-based Doorway Midpoint Detection Errors obtained from Experiment Data

- Due to the **non-ideal** estimation accuracy, there are some ambiguous ranges;

"Step 2" Measurements - Practical Case - Ambiguous Range

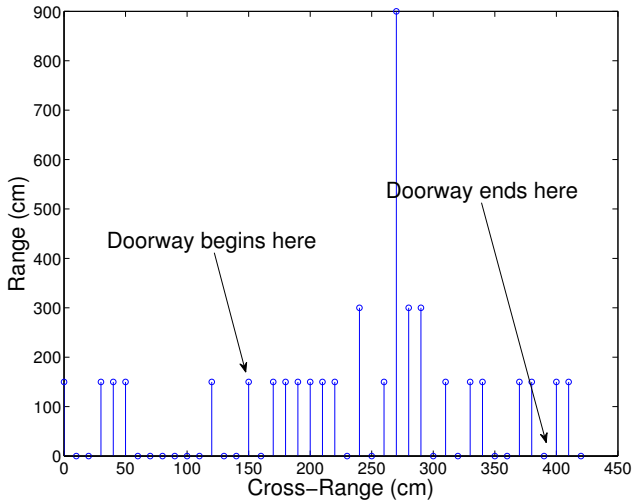
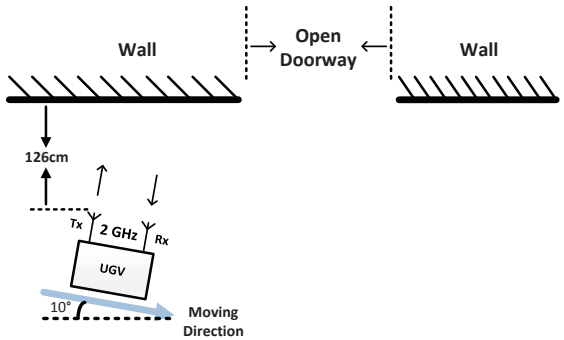


Figure 20 : Power-based Doorway Midpoint Detection Errors obtained from Experiment Data

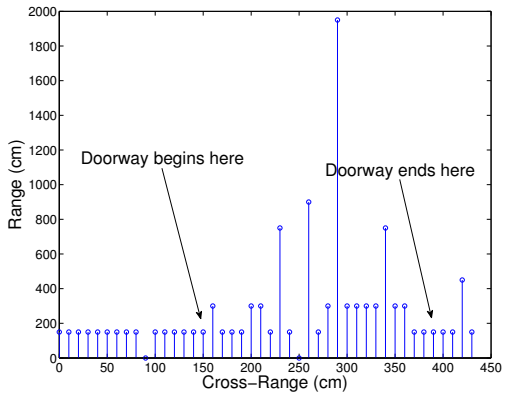
- Due to the **non-ideal** estimation accuracy, there are some ambiguous ranges;
- In our case, **the estimation accuracy** is 150cm so **the ambiguous range** is chosen from the discrete set $\{75cm, 225cm, 375cm, ...\}$;
- The range detection results at these ambiguous ranges **oscillate between two adjacent range values**, e.g. $\{0cm, 150cm\}$ shown in Fig. 20.

"Step 2" Measurements with SRD Errors

"Step 2" Measurements with SRD Errors



(a) Experimental Setup of Detection Measurement with 10° SRD Error at 2 GHz Carrier Frequency

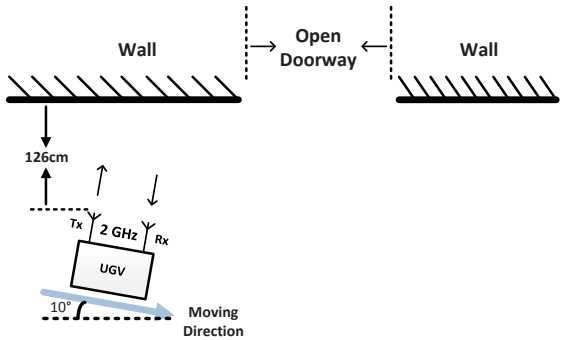


(b) Example of Detection Profile with 10° SRD Error at 2 GHz Carrier Frequency

Figure 21 : Ranging-based Doorway Detection with 10° SRD Error at 2 GHz Carrier Frequency (The range is around 69cm)

- In the case with **SRD errors**, UGV will **not move parallel to the wall**, which results in increased (decreased) ranges to the wall as the cross-range increases;

"Step 2" Measurements with SRD Errors



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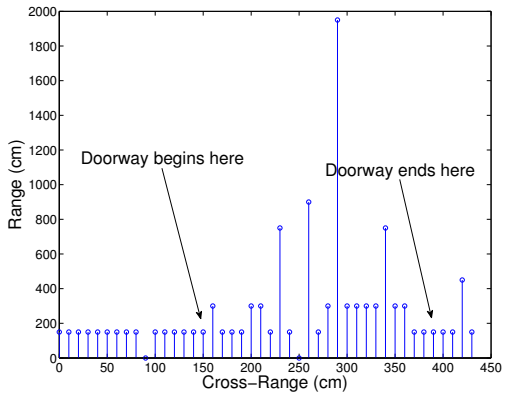

(b) Example of Detection Profile with 10° SRD Error at 2 GHz Carrier Frequency

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- In the case with **SRD errors**, UGV will **not move parallel to the wall**, which results in increased (decreased) ranges to the wall as the cross-range increases;
- As you can see, **ranging-based doorway detection method** is robust to the slight change of range.

Doorway Midpoint Detection Algorithm[5]

[5] Appendix E - Doorway Midpoint Detection Algorithm

Doorway Midpoint Detection Algorithm[5]

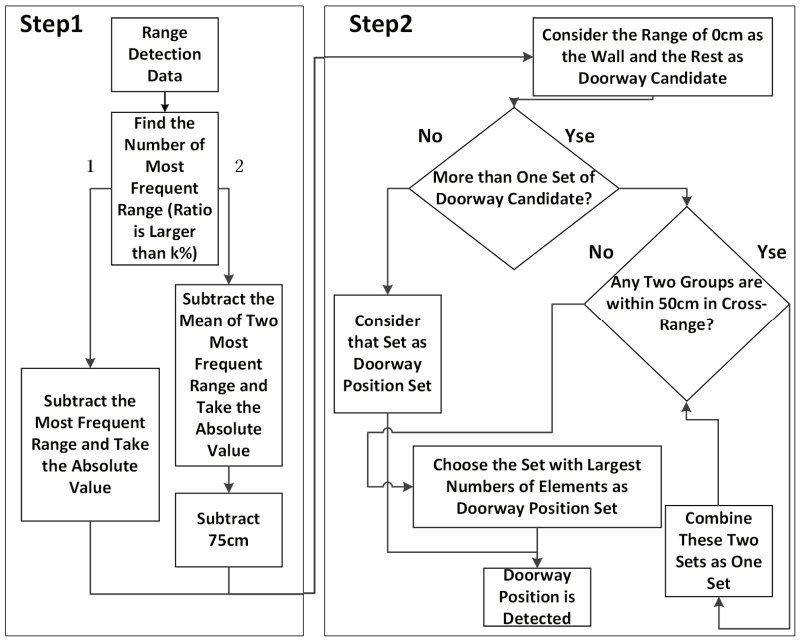


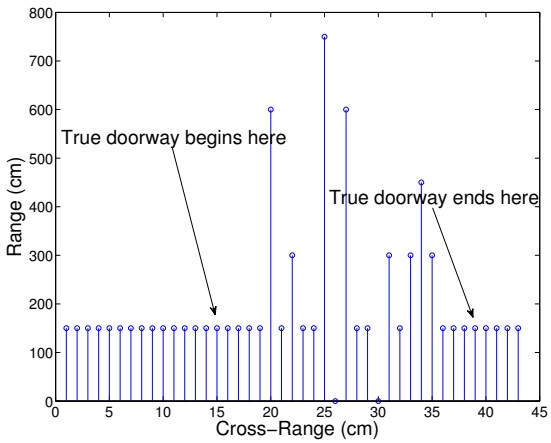
Figure 22 : Doorway Midpoint Detection Algorithm Block Diagram of Ranging-based Doorway Detection

- Based on our experimental experience, while the USRP faces the wall, the range values are usually **sitting around one value** or **oscillate between two nearby values**.

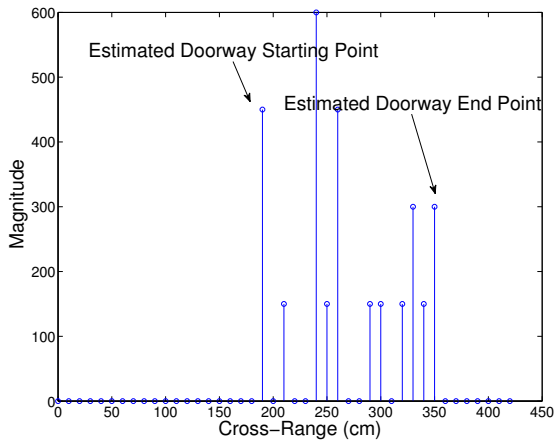
[5] Appendix E - Doorway Midpoint Detection Algorithm

Doorway Midpoint Detection Algorithm - Example 1

Doorway Midpoint Detection Algorithm - Example 1



(a) Detection Profile at 126 cm with 2 GHz Carrier Frequency



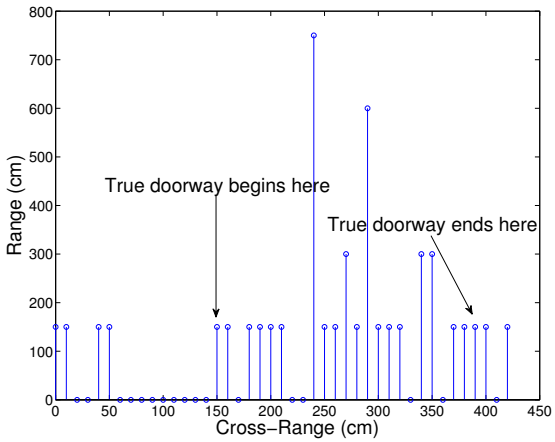
(b) Processed Result at 126 cm with 2 GHz Carrier Frequency

Figure 23 : Ranging-based Doorway Detection Profile and Processed Results

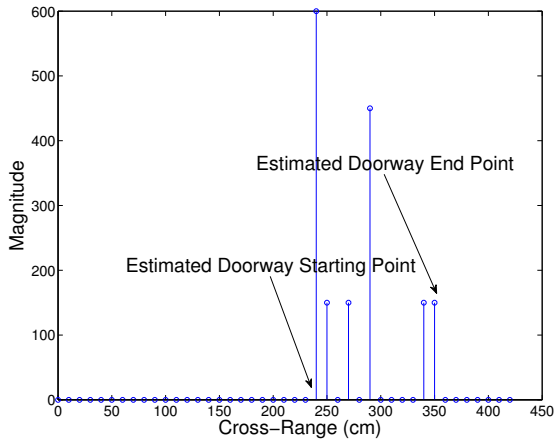
- In this detection profile, the range values are **sitting around 150 cm**;
- **Two adjacent continuous non-zero** sets are recursively combined into one non-zero set and all the zero elements between them are set to be non-zero if the distance between these two sets are smaller than 50cm.

Doorway Midpoint Detection Algorithm - Example 2

Doorway Midpoint Detection Algorithm - Example 2



(a) Detection Profile at 69 cm with 2 GHz Carrier Frequency



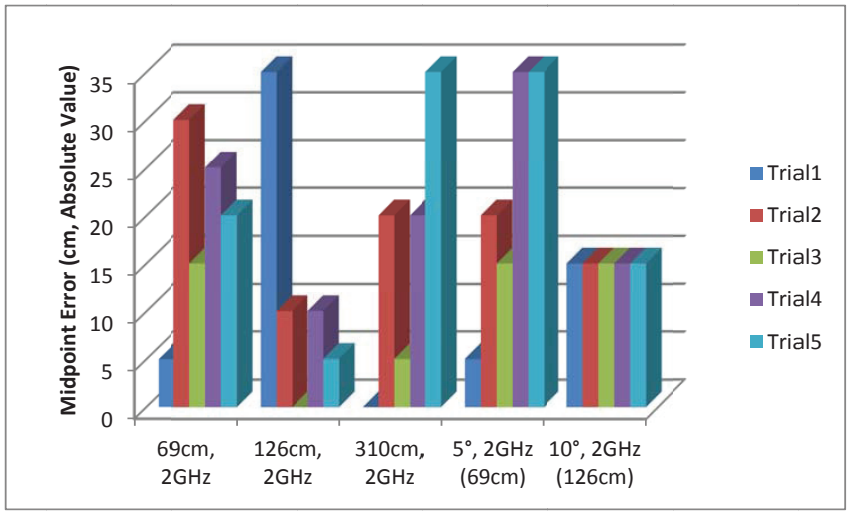
(b) Processed Result at 69 cm with 2 GHz Carrier Frequency

Figure 24 : Ranging-based Doorway Detection Profile and Processed Results

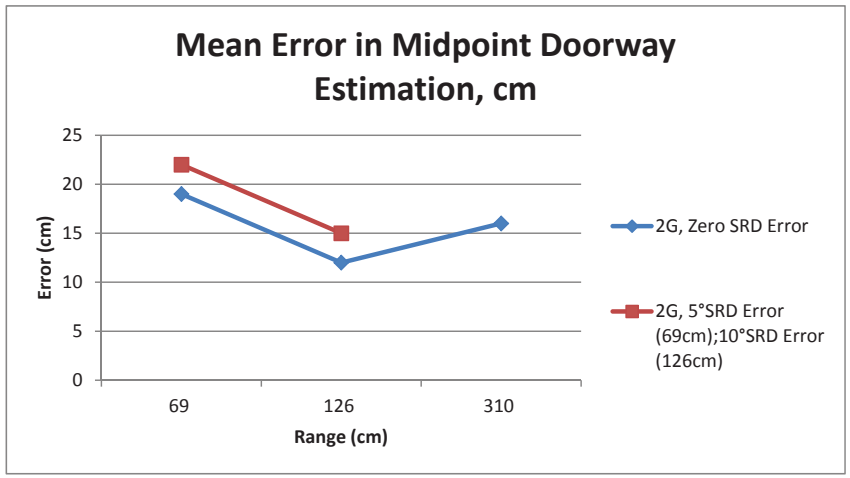
- In this detection profile, the range values **oscillate between two nearby values**;
- **The mean value of these two most frequent values** are subtracted and we take the absolute value of them. Then **75 cm** are subtracted in order to compensate for the difference of these two most frequent values.

Doorway Midpoint Detection Results

Doorway Midpoint Detection Results



(a) Midpoint Detection Errors obtained from Experiment Data



(b) Mean Error in Doorway Midpoint Doorway Estimation

Figure 25 : Doorway Midpoint Estimation of Ranging-based Doorway Detection Algorithm

- There are 25 trials of experiment data collected for **ranging-based doorway detection method**.

Comparison

Comparison

Table 1 : Comparison of Power-based and Ranging-based Doorway Detection Methods

Detection Method	Power-based	Ranging-based
Doorway Midpoint Detection Accuracy	Better	Worse
Promise of Detection Success	No	Yes
Influence of Fading Effect	Severe	Slight
Detection with SRD Error	Sensitive	Robust

Comparison

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- **For power-based doorway detection method**, it is found to have **better** doorway midpoint detection accuracy if the fading effect is mitigated by multi-frequency method; In order to remain **high midpoint detection accuracy**, this doorway detection algorithm may have **low detection success rate**;

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- **For power-based doorway detection method**, it is found to have **better** doorway midpoint detection accuracy if the fading effect is mitigated by multi-frequency method; In order to remain **high midpoint detection accuracy**, this doorway detection algorithm may have **low detection success rate**;
- **For ranging-based doorway detection**, fading effect will only degrade the system performance slightly due to the limitation of ranging resolution. Also, the detection performance strongly depends on **the initial range to the wall** (**Effect of Ambiguous Range**).

Outline

Doorway Detection Procedure[6]

[6] Appendix F - Doorway Detection Procedure

Doorway Detection Procedure[6]

- **Step1: Wall Searching Step** - Finding the closest wall by USRP radar sensing;

[6] Appendix F - Doorway Detection Procedure

Doorway Detection Procedure[6]

- **Step1: Wall Searching Step** - Finding the closest wall by USRP radar sensing;

- **Step2: Wall Approaching Step** - Approaching the closest wall by radar ranging;

[6] Appendix F - Doorway Detection Procedure

Doorway Detection Procedure[6]

- **Step1: Wall Searching Step** - Finding the closest wall by USRP radar sensing;
- **Step2: Wall Approaching Step** - Approaching the closest wall by radar ranging;
- **Step3: Wall Following Step** - Following the wall by IR sensing until an open doorway is detected.

[6] Appendix F - Doorway Detection Procedure

Open Doorway Detection Demonstration

Outline

Conclusion (1/2)

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- **A 2-stage doorway detection procedure** is proposed;

Conclusion (1/2)

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- Two open doorway detection methods, i.e. **power-based doorway detection method** and **ranging-based doorway detection method**, are proposed to perform indoor radar sensing with low cost narrow-band software defined radio USRP;

Conclusion (1/2)

- **A 2-stage doorway detection procedure** is proposed;
- Two open doorway detection methods, i.e. **power-based doorway detection method** and **ranging-based doorway detection method**, are proposed to perform indoor radar sensing with low cost narrow-band software defined radio USRP;
- **In addition**, an open doorway is **autonomously** detected by **a USRP-based radar-guided UGV**.

Conclusion (2/2)

Conclusion (2/2)

Power-based Doorway Detection:

- System performance is degraded by **fading effect**;
- **Frequency domain filtering algorithm** is developed to detect the doorway midpoint.

Conclusion (2/2)

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- System performance is degraded by **fading effect**;
- **Frequency domain filtering algorithm** is developed to detect the doorway midpoint.

Raging-based Doorway Detection

- System performance is degraded by **the limitation of USRP sampling rate**;
- **Ambiguous range** leads to unstable fluctuation when the UGV scans the wall;
- **Proposed ranging-based doorway detection** is able to remove the ambiguity and detect the doorway midpoint.

Conclusion (2/2)

Power-based Doorway Detection:

- System performance is degraded by **fading effect**;
- **Frequency domain filtering algorithm** is developed to detect the doorway midpoint.

Raging-based Doorway Detection

- System performance is degraded by **the limitation of USRP sampling rate**;
- **Ambiguous range** leads to unstable fluctuation when the UGV scans the wall;
- **Proposed ranging-based doorway detection** is able to remove the ambiguity and detect the doorway midpoint.

Comparison

- **Power-based doorway detection method** exhibits better doorway midpoint detection performance than **ranging-based doorway detection method**.

Future Work

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- **Reflection Power Analysis:** We'll analyse **the reason of the fading effect** in the indoor environment theoretically and build **a reflection power model**;

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- **Multi-UGV detection:** **Multi-UGV detection** will be proposed to enhance the system performance;

- **More Sophisticated Detection Algorithm:** **A more robust power-based doorway detection algorithm** will be developed and **combination of these two detection methods** will be proposed.

Outline

Publication

- Y. X. Liu, Y. L. Guan, D. Garmatyuk, Y. J. Morton, "USRP based OFDM radar systems for doorway detection, "in Radar Conference (RADAR), 2014 IEEE, pp. 0875-0880.

Thanks for your time

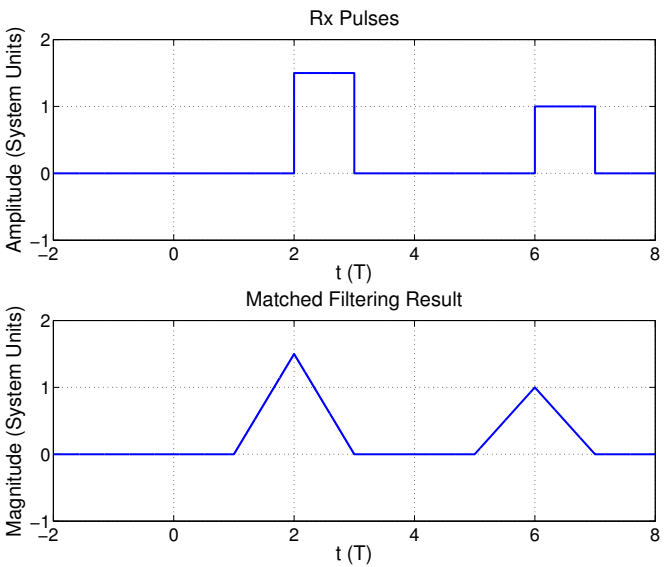
YunXiang LIU, Leo

Appendix A - Radar Basics - Range Resolution

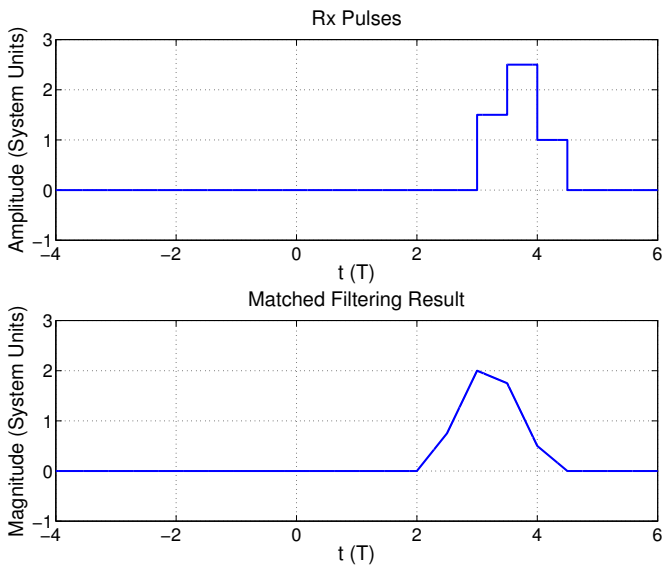
Appendix A - Radar Basics - Range Resolution

Range resolution is the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges [9], which is formulated as:

$$Range_{res} \geq \frac{c \cdot \tau}{2} \tag{4}$$



(a) Two Rx Pulses whoes spacing are Larger than Range Resolution



(b) Two Rx Pulses whoes spacing are Smaller than Range Resolution

Figure 26 : Rx Pulses and Matched Filtering Results

Appendix B - Amplitude and Magnitude

Appendix B - Amplitude and Magnitude

- **The amplitude** of a variable is the measure of how far, and in what direction, that variable differs from zero. Thus, signal amplitudes can be **either positive or negative** [11].

- **The magnitude** of a variable, on the other hand, is the measure of how far, regardless of direction, its quantity differs from zero. So magnitudes are always **positive** values [11].

Appendix C - Radar Equation

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Radar equation describes the relation between the transmitted power, received power and propagation environment. Radar sends out the electromagnetic waves, which are reflected if they meet an electrically leading surface[12]. Once the reflected electromagnetic waves are received again by the radar system, then an obstacle is detected to be present in the transmitting direction. The reflected power is determined by radar equation[13]

$$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R_t^2 R_r^2} \tag{5}$$

where P_t is the transmitter power, and G_t is gain of the transmitting antenna. Effective aperture (area) of the receiving antenna is denoted as A_r while σ is the radar cross section, or scattering coefficient, of the target. Meanwhile, F is the pattern propagation factor. R_t and R_r denote distance from the transmitter to the target and distance from the target to the receiver respectively.

Appendix D - Interpolation

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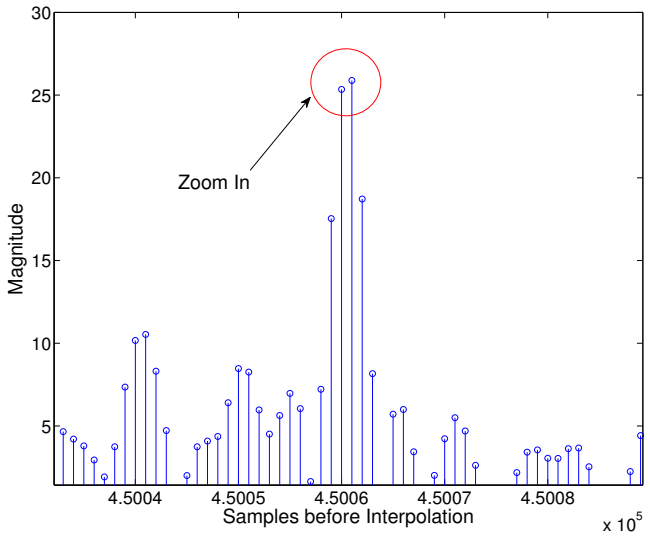
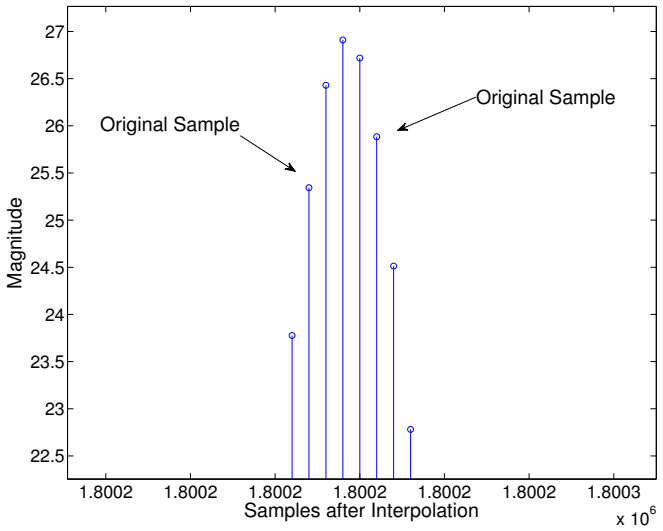


(a) Cross-Correlation Profile before Interpolation



(b) Cross-Correlation Profile after Interpolation

Figure 27 : Synchronization of the OFDM Short Preamble based on Experiment Data

- **The interpolation operation** gives a more accurate estimation.

Appendix E - Doorway Midpoint Detection Algorithm

Appendix E - Doorway Midpoint Detection Algorithm

- **Step 1:** We find the 1 or 2 most frequent range values, which is chosen to be the one whose occupying ratio is more than k%, which is normally chosen to be 20 based on our experimental experience. Then we subtract the value of the (or mean of these two) most frequent value (values) and take the absolute value operation for the result. **If the number of most frequent value is 1**, we directly come to Step 2. **If the number of most frequent values is 2**, we subtract 75 cm from the absolute value in order to compensate for the difference of these two most frequent values.
- **Step 2:** Now we assume that the number of 0 represents the wall while the rest continuous non-zero values form **the doorway location candidate set**. Two continuous non-zero sets are **recursively combined** into one non-zero set and all the zero elements between them are set to be non-zero **if the distance between these two sets are smaller than 50cm**. Once all the combinations finish, if there are still two or more candidate sets, then we choose the set with largest number of non-zero values as the doorway.

Appendix F - Doorway Detection Procedure

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- **Wall Searching Step:** **SRD** is performed. UGV is rotated one cycle 360° with fixed step size (e.g. 5°) in place, in order to find **the direction nearest to the wall**;

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- **Wall Searching Step:** **SRD** is performed. UGV is rotated one cycle 360° with fixed step size (e.g. 5°) in place, in order to find **the direction nearest to the wall**;

- **Wall Approaching Step:** **Radar ranging** is performed. The UGV will be moved forward in steps until **the detected range** is 0 meter. **However**, the range estimation accuracy is 1.5 meters, which is quite large. In order to bring the UGV as close to the wall as possible, we may ask the UGV to **move forward further** for another 0.75 meter when 0 meters is detected **for the first time** (because now the distance is around 0.75 meter instead of 0 meter).

Appendix F - Doorway Detection Procedure

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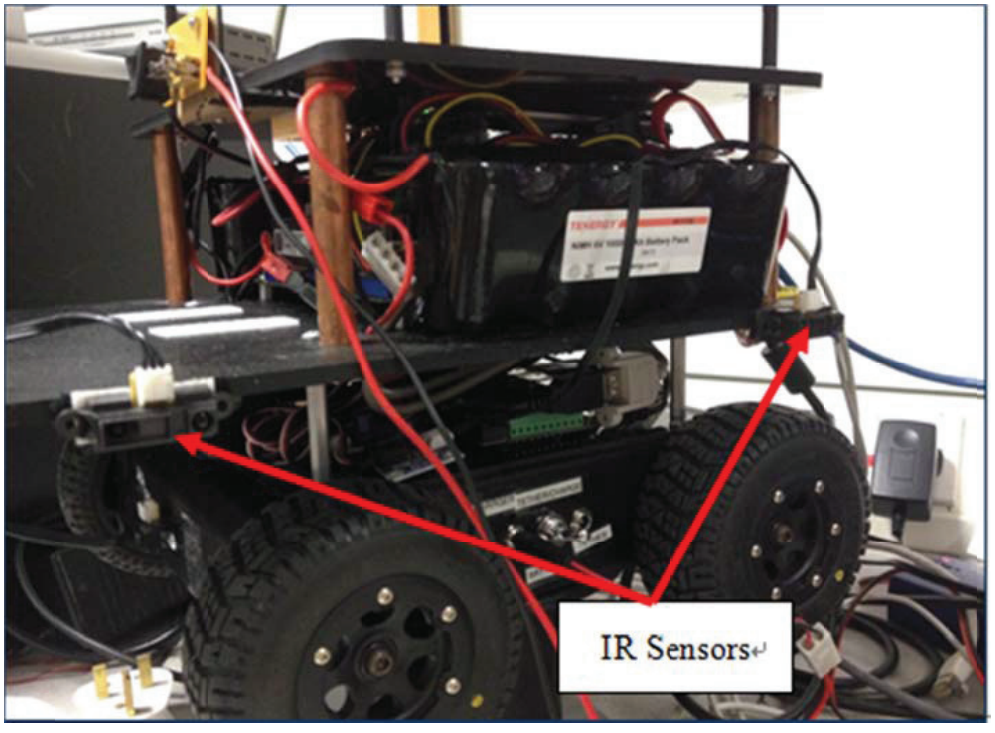

Figure 28 : IR Sensors for Wall Following Step

Wall Following Step:

- These two **IR sensors** are both placed at the left side of the UGV which is shown in Fig. 28.

Appendix F - Doorway Detection Procedure

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Wall Following Step:

- **Theoretically**, UGV is parallel to the wall if both wall searching step and wall approaching step are perfectly performed;
- **However**, there are lots of rotation error in the previous two steps;
- **Hence** to avoid the collision with the wall or being too far away from it, **a wall following algorithm** needs to be developed to keep the UGV moving forward along a path which is roughly parallel with the wall.

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- **Theoretically**, UGV is parallel to the wall if both wall searching step and wall approaching step are perfectly performed;
- **However**, there are lots of rotation error in the previous two steps;
- **Hence** to avoid the collision with the wall or being too far away from it, **a wall following algorithm** needs to be developed to keep the UGV moving forward along a path which is roughly parallel with the wall.

Wall Following Algorithm:

- To achieve this target, two **IR sensors** are utilized;
- They are designated to face the wall and detect **the distance to that wall**;
- When the detected distance of two sensors are **different**, the UGV makes adjustment in its steering direction to render the UGV **as parallel to the wall as possible**.

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