CONTENTS

LIST OF USED ABBREVIATIONS

ACD – Actuator Control Device

ADC – Analog-to-Digital Converter

BLDC – Brushless DC motor

CAN – Controller Area Network

DC – Direct Current

DMA – Direct Memory Access

FOC – Field Orientated Control

GDP – Gross Domestic Product

GPIO – General Purpose Input/Output

HAL – Hardware Abstraction Layer

I2C – Serial asynchronous bus

LED – Light Emitting Diode

MC – Microcontroller

MCU – Microcontroller Unit

MOSFET – Metal-Oxide Field-Effect Transistor

PID – Proportional-Integral-Derivative controller

PLL – Phase-Locked Loop

PWM – Pulse Width Modulation

SCD – Strategic Control Device

SPI – Serial Peripheral Interface

SSH – Secure Shell

SVPWM – Space Vector Pulse Width Modulation

TCD – Tactical Control Device

UART – Universal Asynchronous Receiver/Transmitter

UVLO – Under Voltage Lock Out

kOPS – Thousand Operations Per Second

INTRODUCTION

1 RESEARCH BACKGROUND AND JUSTIFYING THE TOPIC

1.1. Background and Motivation

Until recently, radar technology was primarily associated with high-end vehicles and military applications. However, today, the same technology is being used in everyday objects such as table lamps and smart speakers.

For instance, the **?** home presence sensor is capable of detecting up to five individuals and responding to their movements, all while remaining unobtrusive and serving as an alternative to traditional surveillance methods.

The development and production of mobile robots is currently a rapidly growing field. Such robots are used both in the industrial sector and in everyday life. Research and development of mobile robots is being actively carried out to eliminate the consequences of natural and man-made disasters, for the needs of the military-industrial complex and space research. In this regard, the creation of mobile robots is not only a commercially profitable and scientifically significant direction, but also a strategically important task for the state and society as a whole.

The history of their evolution reflects the achievements in the field of robotics. The list summarises the key milestones in the speed increase of mobile robots and the specifics of their applications. The increasing speed of mobile robots inevitably leads to increasing demands on their internal systems. This applies both to the power of actuators, the accuracy of sensor systems, and control algorithms(**?**).

Traditionally, robotic systems have relied on light sensors such as cameras and lidars to build a view of the environment. Unfortunately, cameras and lidars are not universally functional when faced with illuminated or structurally degraded cases. Despite consistent developments on photometric calibration(**?**), camera distortion calibration (**?**)

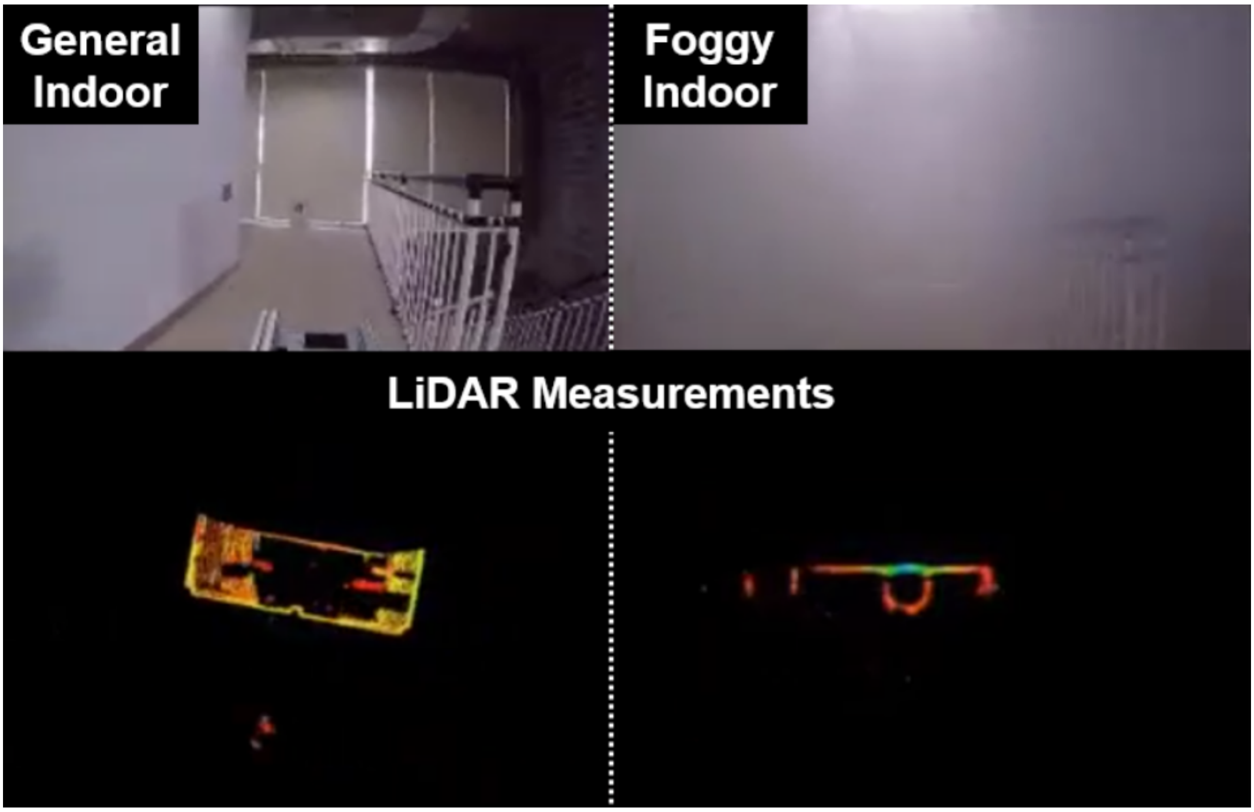

Figure 1.1. Lidar measurements in a foggy indoor environment (?)

Navigational situations that seriously impair the camera (?) and lidar (?) as seen on figure 1 but not the radar include smoke, dust, fog, rain, and snow. Radars can theoretically pass through the different types of tiny particulate matter by using longer wavelengths.

Radar technology, although widely used in meteorology, target tracking, planetary mapping, and automotive safety, remains underutilized in robotics compared to shorter wavelength sensors like cameras and lidars. Radar systems transmit and receive specially shaped electromagnetic pulses to determine the distance and direction of objects, offering advanced sensing capabilities. This makes radar a valuable option for integration with existing systems or as an independent sensor, enabling robots to perform both metric and semantic tasks reliably.

The advent of mWave radars operating in the 76–81 GHz range provides a compact and alternative to lidar .

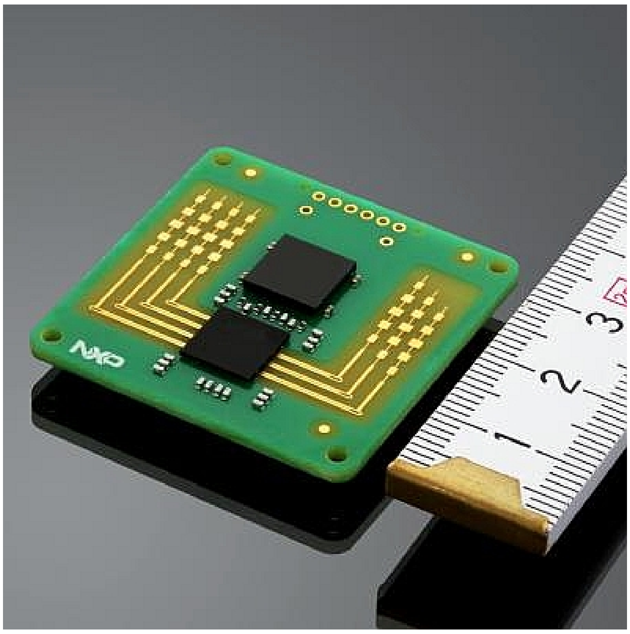

Figure 1.2. Radar sensors (?)

In recent years, there has been a significant increase in the number of devices utilizing millimeter-wave (mmWave) radars. Most existing solutions are represented by radar-on-chip systems. A radar-on-chip is an integrated system that combines radar functionality into a single compact microchip device (Figure 1.2), making it applicable in various fields. Recent developments are focused on replacing presence sensors (PIR), with the primary goal being the detection of humans.(?).

However, there are some reasons why robotics does not frequently use millimeter wave radars. Radar has numerous issues that need to be taken into account while creating new solutions, just like any other sensor. False reflections beyond the sensor's range, more intricate speckle noise, and multipath reflections—which produce several reflections from a single object—are just a few of the distinctive noise features of radar.

Clustering-based filtering algorithms, such CFAR (?), OPTICS (?), and DBSCAN (?), assist in reducing unwanted reflections and speckle noise, although require to be carefully tuned to fit particular hardware and antenna radiation patterns. Enhancing radar sensors themselves with greater resolution and quicker scanning rates can help with this to some extent. However, using various map formats, features, and internal state estimators also allows for algorithmic improvements.

The use of radar sensors in autonomous robots is an optimal solution because a robot is typically a complex collection of different systems. With other sensors, such as inertial sensors or odometers, the robot can determine its current speed, making it much easier to integrate and work with new types of sensors, including radar sensors. This allows for more reliable and accurate perception of the environment.

1.2. Problem Statement

1.3. Research Aim and Objectives

The aim of the work is to develop the principles of construction, as well as the algorithmic and software of the information radar system of a mobile robot.

Research Objectives An information system for detecting and tracking fast-moving objects in robotics applications.

Research Subject Mathematical models of navigation processes for the detection of selected dynamic objects using FMCW radar systems.

1.4. Research Questions and Hypotheses

1.5. Tasks

1.6. Scope and Delimitations

2 STATE OF THE ART

2.1. Introduction

2.2. Range Sensing Technologies

Autonomous vehicles: In the automotive industry, millimeter Wave radars have been incorporated for decades – they act as the vehicle's "distant eyes" for advanced driver assistance systems (ADAS). A classic example - cruise control with radar: the front-mounted radar continuously measures the distance and speed of vehicles ahead, allowing the system to automatically adjust speed and maintain a safe distance. Radars are also employed for emergency braking in the event of obstacles, monitoring "blind spots". For instance, Tesla (until 2021), combined a front-facing 77 GHz radar with cameras, while many other manufacturers have added multiple radars around the vehicle for a comprehensive view.

For research purposes: the **Oxford RobotCar** project at Oxford University has garnered significant attention – a 2D laser (lidar) and a specialized 76 GHz frequency-modulated continuous wave (FMCW) radar (**Navtech CTS350-X scanning system**) have been installed on an unmanned standard vehicle.(**?**) This radar system rotated 360 degrees, similar to a lidar system, and provided a radar image of the surroundings with a resolution of approximately **0.9 degrees** at a distance of **163 meters** . As a result, also a large dataset was collected for the **Oxford Radar Robot Car**. All sensors (camera, lidar, radar, and odometry) were recorded simultaneously as the vehicle traveled around the city. This experiment confirmed that radar is suitable for large-scale urban mapping and navigation and remains operational even in challenging conditions such as rain, nighttime, and difficult lighting. Subsequently, several studies have been conducted using this data to develop algorithms for localization and obstacle avoidance based on radar images.

Other platforms: Millimeter wave radars are of interest for various applications, including unmanned aerial vehicles (UAVs), robotic manipulators, and humanoid systems. For instance, in the case of flying UAVs, radars can provide a stable measurement of height above the ground and the detection of obstacles, such as smoke or dust, which is relevant for fire reconnaissance missions. In the **DARPA Subterranean Challenge** event, some teams have experimented with radar technology to navigate through smoke-filled tunnels, where lidar sensors may not be effective. (**?**) In humanoid robots, radars can help detect the presence and movement of people or objects that may be outside the range of camera vision. Texas Instruments has demonstrated a prototype that uses a radar system located in the chest of the robot to detect the presence of a person and their movement, allowing the robot to react accordingly, even in worse light conditions.(?)

In industrial robotics: automated guided vehicles (AGVs) in factories and warehouse robots, radars are implemented to enhance safety. For instance, 60-64 GHz radar systems monitor the area surrounding a forklift truck, detecting people or other machinery and stopping the robot if a path is blocked.(?) This technology can be applied across a wide range of platforms, from small household robots to vehicles, depending on their unique sensing capabilities.

2.2.1. Lidar

2.2.2. Optical Sensors

2.2.3. Radar Sensors

2.2.4. Acoustic Sensors

2.3. Motion Planning

2.3.1. Pathfinding

2.3.2. Motion Planning

2.3.3. SLAM

2.4. Synthesis and Research Gaps

3 METHODOLOGY & DEVELOPMENT EQUIPMENT

3.1. Research Design/Approach

3.2. Data Collection/Experimental Setup

3.3. Robot Platform

3.4. ROS2

4 RADAR ANALYSIS

4.1. Rationale for the selection of Radar

Several frequency bands within the mmWave spectrum are utilized for radar applications, each offering distinct characteristics relevant to robotics:

24 GHz Band: This band is often associated with lower system costs. However, it typically provides less bandwidth (e.g., around 250 MHz, though wider bandwidths up to 1 GHz or more are possible in some regions/applications) compared to higher frequency bands. This limited bandwidth restricts the achievable range resolution and accuracy.7 Despite this, 24 GHz radars are employed for applications like presence detection and in some older or lower-cost automotive systems.

60 GHz Band: The 60 GHz band offers wider bandwidths, with some systems utilizing up to 7 GHz.7 This wider bandwidth translates to a degree of precision and range resolution, making it applicable for short-range sensing applications where detailed environmental perception is needed. Such applications include gesture recognition, vital signs monitoring, and, increasingly, robotic perception for tasks like detailed mapping and obstacle avoidance in cluttered spaces.7 A notable characteristic of the 60 GHz band is its susceptibility to higher atmospheric absorption, primarily due to oxygen molecules.13 While this can limit the maximum operational range, it also serves to reduce interference between nearby 60 GHz radar systems, which can be a feature in environments with multiple robots or sensors.

77-81 GHz Band (often referred to as 77 GHz or 76-81 GHz): This band has become the standard for automotive radar, underpinning Advanced Driver-Assistance Systems (ADAS) and autonomous driving functionalities. Its widespread adoption is driven by the availability of large bandwidths (e.g., 4 GHz or more 7), which enable a degree of resolution and accuracy for longer-range object detection and tracking.2 The performance characteristics of this band make it applicable for robots requiring long-range perception.

4.2. Features of radar signals

4.2.1. FMCW features in radar systems

4.2.2. Pulse compression

4.2.3. Frequency modulation

4.2.4. Pulse repetition frequency

4.2.5. Bandwidth

4.2.6. Resolution

4.2.7. Range

4.3. Radar connection diagram

4.4. Comparison of Radar System Parameters

5 RADARS DATA PROCESSING ANALYSIS

5.1. Detection environment

5.2. Parameterization of the radar system

5.3. Program implementation

5.4. Results of the experiments

6 UTILIZATION FOR ROBOT MOTION PLANNING

6.1. Robot Platform

6.2. Tasks and scenarios

6.3. Architecture of the motion planning system

6.3.1. Software architecture

6.3.2. Algorithm implementation

6.4. Experimental results

7 EXPERIMENTAL RESULTS AND ANALYSIS

7.1. Radars Data Processing Analysis

8 CONCLUSION

8.1. Utilization for Robot Motion Planning

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