Dragonfly Quadrotor UAV
Flight Control Board

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Introduction

The *Dragonfly* project is an internal competence enhancement project for ÅF employees. The goal is to combine technology, competence and experience from various engineering fields in order to construct a highly advanced quadrotor UAV system. The focus of the Flight Control Board development deals with low-level maneuvering of the aircraft, calculating motor command based on a feedback control system. Some of the major technologies deployed to attain this are control theory, electronics and software development.

An early CAD rendeded image of the Dragonfly quadrotor concept can be viewed in Figure 2.1.

Figure 2.1: Rendered image of one of the first quadrotor designs concepts

Part I

Theory

Chapter 3

Introduction

This part concerns the physical, mathematical and control system theory essential to understand the quadrotor system sufficiently to control its flight. The flight theory presents a rigid-body dynamical model of the quadrotor flight as well as representation of coordinate systems suitable to present aircraft states such as position, attitude and velocity. Aerodynamic effects on this system is also presented and discussed. For the control part, the problem of controlling the aircraft is split in to two distinct parts - estimating the current states and controlling the system to achieve desired states.

Chapter 4

System Description

4.1 Coordinate System Representation

World-frame and body-frame coordinate systems. Euler angles and rotation matrices. Transformations between coordinate frames.

4.2 Flight Dynamics

4.3 BLDC Motor Theory

Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor. In this context, AC, alternating current, does not imply a sinusoidal waveform, but rather a bi-directional current with no restriction on waveform. Additional sensors and electronics control the inverter output amplitude and waveform (and therefore percent of DC bus usage/efficiency) and frequency (i.e. rotor speed).

Electrical motors are based on interaction between two magnetic fields, one produced by a permanent magnet and one by current flowing in the motor windings. The fields produce a torque which drives the rotor. During rotation, the current in the winding is commutated (reversed) to obtain a continuous torque.

The BLM motors used for this project have an "outrunner" architecture, which means that the permamagnet rotor lies outside the winding stator. The windings are separated into several coils energized cyclically (AC current) by an electronic speed controller (ESC) to achieve rotor rotation.

4.4 Radio Control Theory

4.5 Sensor Theory

4.5.1 Microelectromechanical Systems (MEMS) Sensors

4.5.2 Gyroscope

4.5.3 Accelerometer

4.5.4 Magnetometer

Chapter 5

State Estimation Theory

5.1 Attitude Estimation

5.2 Velocity Estimation

Chapter 6

Flight Control Theory

6.1 Controller Design

Figure 6.1 shows an overview of the control problem.

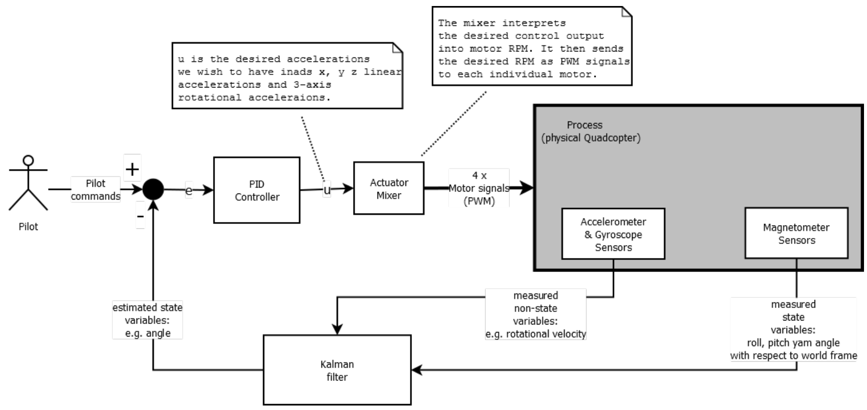

Figure 6.1: Control overview diagram

PID controller equation presented in (6.1), where $u(t)$ is the control signal and $e(t) = y_{ref}(t) - y(t)$ is the control error.

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^{\infty} e(t)dt + T_d\frac{d}{dt}e(t)\right) \tag{6.1}$$

6.2 Attitude Control

6.3 Velocity Control

Chapter 7

Sensor Calibration Algorithms

7.1 Gauss-Newton Optimization

7.2 Magnetometer calibration

7.3 Accelerometer calibration

Part II
Implementation

Chapter 8

Introduction

In this part, the implementation of the flight control system is presented and discussed. It concerns documentation of both electronic and software design choices. The heart of the flight control system is the *Flight Control Board* (FCB) program, running on an STM32F303VC microcontroller attached to an STM32F3Discovery board featuring on-board sensors, debug interface and more. The program is mainly written in C code and executes code to, among other things, control and actuate the motors, read from the sensors and an RC receiver and estimate the flight states.

Chapter 9

Hardware

9.1 Flight Control Board - STM32F3Discovery

The STM32F3Discovery is an evaluation board provided by STMicroelectronics. It features an STM32F303VCT6 microprocessor based on the ARM Cortex-M4 core. For evaluation purposes, the board has been fitted with accelerometer, magnetometer and gyroscope sensors, an on-board ST-Link/V2 debugger/programmer, various LED:s, extension headers for all I/O pins and more.

- CPU speed: 72 MHz
- ROM: 256 kB Flash
- RAM: 48 kB (40 kB SRAM, 8 kB CCM)
- I/O pins: LQFP100 pin package with pins attached to extension header
- On-board ST-LINK/V2 programming and debugging device
- Power supply: From USB bus or from an external 3 V or 5 V supply voltage
- L3GD20 MEMS gyroscope
- LSM303DLHC MEMS accelerometer and magnetometer
- 10 LEDs
- Two pushbuttons
- USB USER Mini-B connector

Figure 9.1 shows the microcontroller internal bus matrix, connecting the core to the MCU peripherals.

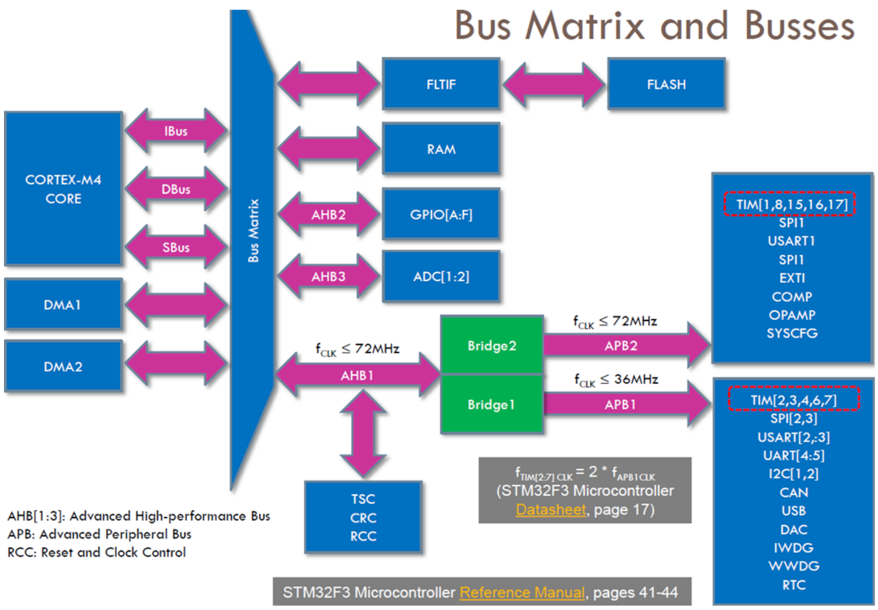

Figure 9.1: STM32F3 bux matrix

9.2 T-Motor U3 BLDC Motors

The motors of choice for the Dragonfly are of the type *T-motor U3*, which are sensorless (no built-in Hall sensor) brushless motors, designed to deliver high performance and reliability. According to the manufacturer, they are highly resistant to dirt and water. There are several benefits of using brushless motors instead of traditional DC motors, including longer life-time (due to no brushes that become worn out), less noisy operation and more efficient cooling.

The T-motor U3 motors have 12 stator coils and 14 rotor magnets. The motor theory was earlier presented in Section 4.3.

- Motor velocity constant: 700 rpm/V
- Stator-pole configuration: $12N - 14P$
- Dimensions: Diameter: 41.80 mm, Height: 30.75 mm
- Weight: 97 g
- Idle current: 0.5 A
- Recommended number of battery cells (LiPo): $3 - 4S$
- Max continuous current (180 s): 25 A
- Max continuous power (180 s): 400 W
- Max current efficiency: $(4 - 10\ A) > 82\ \%$
- Internal resistance: 50 $m\Omega$

Figure 9.2: T-Motor U3 BLDC motors

Throttle %	**Current** $[A]$	**Power** $[W]$	**Thrust** $[g]$	**Speed** $[rpm]$	**Efficiency** $[g/W]$
50	3.2	48	460	5300	9.58
65	6.0	87	710	6500	8.16
75	8.2	120	870	7500	7.25
85	11.0	160	1080	8200	6.75
100	13.0	193	1230	8700	6.37

Table 9.1: T-Motor U3 motor with 11x3.7 inch CF propeller data

The motor and propeller manufacturer, T-motors, provides some information on the actuation characteristics in Table 9.1. The values were obtained with an operating temperature of 43° C with 11x3.7 inch T-motors carbon fibre propellers attached to the motor shaft.

9.3 T-Motor ESC30A Electronic Speed Controllers

Motor speed control is achieved using ESCs, which cyclically shift the coils' current by applying a three-phase alternating-current. So the motors themselves are really AC motors, although driven by a DC power source (battery).

The battery drain is determined using MOSFET transistors. By feeding an ESC with a pulse-width modulated (PWM) signal, battery power is switched on and off rapidly for periods decided by the PWM duty cycle. Since this is done at a sufficiently high frequency, the supplied current (which is modulated to AC) "seen" by the motors can be approximated to the mean battery drain. So, the higher the duty cycle the more battery drain and the higher larger electromagnetic torque generated in motor.

The ESCs of choice for this project is the *T-Motor ESC30A*, shown in Figure 9.3. It takes a PWM input signal up to 400 Hz to drive the motors. Normally in RC applications, a 1 ms pulse width indicates 0 % throttle, whereas 2 ms is 100 % throttle (with 50 % being approx. 1.5 ms). The ESCs feature BEC (Battery eliminator circuit), which outputs a low-power 5 V source useful to power onboard electronics.

- Output: Continuous 30A, Burst 40A up to 10 Secs.

Figure 9.3: T-Motor ESC30A Electronic Speed Controller

- Input: 2-4 cells lithium battery or 5-12 cells NiCd/NIMh battery.
- BEC: 2 A / 5 V (Linear mode)
- Max speed: 35000 rpm for BLDC motor

9.4 RC Receiver and Transmitter

The Spektrum AR610 receiver, shown in Figure 9.4, employs full-range 2.4 GHz DSMX modulated radio communication. It is capable of reading and outputting up to 6 channels of controller information. The output from each channel consists of a PWM signal with a period of 22 ms (approx. 45.45 Hz) with a pulse width between (approx.) 1 and 2 ms, depending on controller action. There is also an additional receiver output, used for binding the controller with the receiver. The channels are labeled as follows:

- BND/DAT (Bind) - Used only to bind the controller to the receiver with the bind plug (see image). More on this can be found in the controller and/or receiver manuals.
- THRO (Throttle) – Typically used to control the altitude actuation.
- AILE (Aileron) – Typically used to control the roll actuation.
- ELEV (Elevator) – Typically used to control the pitch actuation.
- RUDD (Rudder) – Typically used to control the yaw actuation.
- GEAR – Open to interpretation
- AUX (Auxiliary) - Open to interpretation.

Figure 9.4: Spektrum AR610 receiver

The RC transmitter of choice is the Spektrum DX6i, which is a 6-channel transmitter using 2.4 GHz Spektrum DSMX modulation. In Figure 9.5, the transmitter's stick and switch mapping and labeling is shown.

MCU Timer Input Compare registers are configured and used to read input PWM signals, typically from the RC receiver. They are connected to timer channels to generate interrupts on up and down flanks of PWM pulses (the polarity is reversed after reading each flank).

9.5 Battery

The battery used is of Lithium polymer type, containing Lithium ions to drive current from the positive to the negative electrode through a closed circuit.

- Capacity: 8000 mAh
- Voltage: 14.8 V

9.6 Sensors

L3DG20 Gyroscope over SPI. LSM303DLHC over I2C. Orientation with respect to quadrotor coordinate axes.

Figure 9.5: Spektrum DX6i RC transmitter labels

Chapter 10

Software

10.1 System Design Overview

An overview of the entire software architecture can be viewed in Figure 10.1 below. This document mainly concerns the Flight Control Board development.

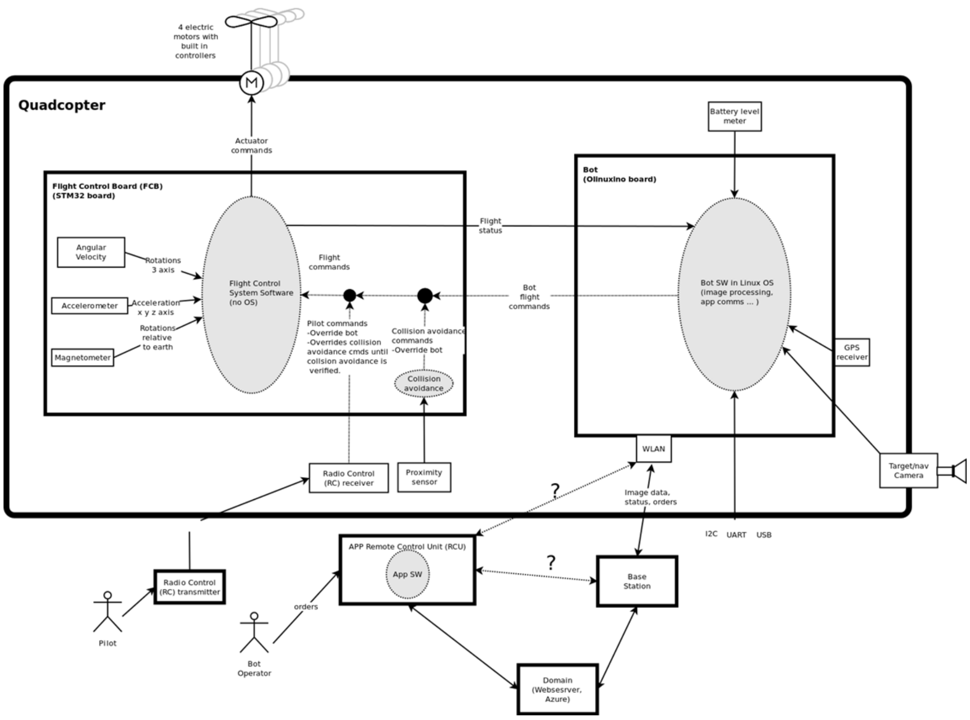

Figure 10.1: Overall software architecture

As can be viewed in the digram in Figure 10.2, the Flight Control Board software takes input from a number of sources. Internally, it receives data from the built-in sensors (gyroscope, accelerometer, compass), whereas external commands are received from the Bot SW (Olinuxino board) as well as the radio-controller (RC) receiver. By applying control and output mixing logic (which will be discussed further on), appropriate motor command signals are generated. These are fed to the Electronic speed controllers (ESC), which in turn provide motor actuation. Since the ESCs used on the Dragonfly provide Battery eliminator circuit (BEC) capability, they are able to provide power (5 V) to the FCB and receiver.

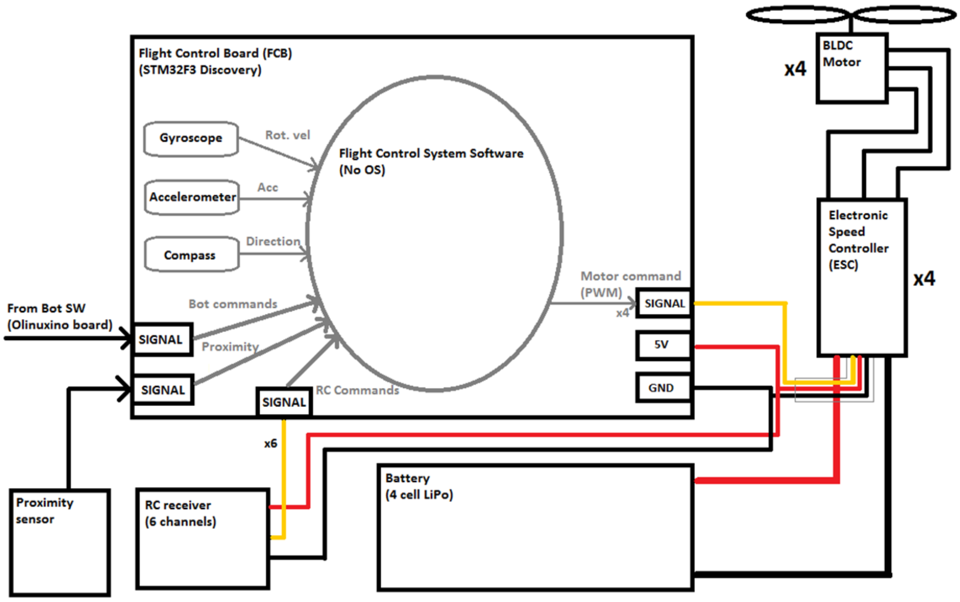

Figure 10.2: FCB software architecture and circuit routing overview diagram. Red lines are 5 V, black are ground and yellow are signals.

10.2 Real-time Design

10.3 Code Documentation

10.3.1 CMSIS

10.3.2 STM32F3xx HAL Drivers

STMicroelectronics provides an extensive library simplifying application interaction with the low-level registers of the MCU. These are known as the Hardware Abstraction Layer (HAL) Drivers, which are a part of the STM32Cube software development package. More detailed documentation on the HAL Drivers library can be found in [6].

10.3.3 STM32 USB Device Drivers

10.3.4 STM32F3Discovery Board-specific Package

10.3.5 FreeRTOS

10.3.6 FreeRTOS Plus CLI

10.3.7 FCB Control

10.3.8 FCB Communication

10.3.9 FCB Sensors

10.3.10 FCB Utilities

10.3.11 NanoPB Protocol Buffer

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