BAB V
PENUTUP

V.1 Kesimpulan

Berdasarkan hasil perancangan, implementasi, dan serangkaian pengujian yang telah dilakukan pada sistem MediBox-*Drone* (Medical *Drone* with Secure Box System) dengan integrasi antarmuka HTML, dapat ditarik kesimpulan sebagai berikut:

1. Implementasi *Drone Board* Berhasil: Perancangan dan implementasi PCB *Drone Board* modular telah berhasil divalidasi melalui pengujian kontinuitas elektrik pada seluruh port JST GH, memenuhi tujuan penyederhanaan *wiring* dan kemudahan instalasi/maintenance.
2. Integrasi ROS 2 dengan PX4 Sukses: Sistem berhasil mengintegrasikan ROS2 *Humble* dengan *flight controller* PX4 menggunakan *middleware* Micro XRCE-DDS melalui koneksi *radio telemetry*. Keberhasilan koneksi *bridge* divalidasi melalui status terminal, memungkinkan kontrol dan monitoring *Drone* dari *Companion Computer*.
3. Fungsionalitas GCS Tervalidasi: Antarmuka *Ground Control Station* (GCS) berbasis HTML berhasil diimplementasikan dan terhubung ke ROS 2 melalui *Rosbridge Websocket*. Seluruh 16 fitur utama, termasuk kontrol manual, manajemen misi *Waypoint*, dan *data logging*, terbukti fungsional dan responsif berdasarkan tabel pengujian, memungkinkan operasi dan pemantauan *real-time*.
4. Sistem Keamanan MediBox Fungsional: Implementasi sistem kunci otomatis pada *Medical-Box* menggunakan motor servo yang dikontrol via ESP32 berhasil divalidasi fungsionalitasnya melalui tombol "Toggle Lock" pada GCS.
5. Kinerja Misi Otonom Tervalidasi (Simulasi): Pengujian simulasi Gazebo menunjukkan tingkat keberhasilan misi 100% untuk skenario 5 *Waypoint* termasuk *multi-landing*. Akurasi navigasi antar *Waypoint* menunjukkan *error* posisi total (E_{pos}) berkisar antara 1.35 m hingga 1.57 m. Akurasi pendaratan bervariasi, dengan error 0.84 m pada *multi-landing* dan 2.06 m pada pendaratan final. Analisis menunjukkan error pada sumbu Y menjadi kontributor dominan

(rata-rata absolut ~1.45 m saat navigasi dan -2.05 m saat pendaratan akhir) , sementara sumbu X (rata-rata absolut ~0.16 m) dan Z (rata-rata absolut ~0.08 m saat navigasi) lebih akurat. Hasil ini divalidasi terhadap *baseline* uji terbang awal (sebelum integrasi) yang memiliki *error landing* antara 27 cm hingga 119 cm.

6. Kinerja Komunikasi: Pengujian *Quality of Service* (QoS) menunjukkan komunikasi melalui USB/FTDI ("Sangat Bagus") lebih unggul dalam hal latensi dibandingkan *radio telemetry* ("Cukup Bagus") berdasarkan standar TIPHON, meskipun keduanya valid untuk digunakan.

Secara keseluruhan, penelitian ini berhasil merancang bangun dan mengintegrasikan sistem *Drone* medis modular yang terkontrol melalui ROS2 dengan antarmuka web fungsional, serta berhasil memvalidasi kinerja sistem melalui simulasi dan pengujian komponen, yang menunjukkan potensi peningkatan fungsionalitas kontrol dan pencatatan data misi. Ini menunjukkan hasil yang positif untuk penerapan *Drone* medis ke daerah terpencil secara otonom tanpa andil manusia secara langsung.

V.2 Saran

Berdasarkan kesimpulan yang diperoleh, berikut adalah beberapa saran untuk pengembangan sistem *MediBox-Drone* di masa mendatang:

1) Optimalisasi Kontroler Sumbu Y: Mengingat adanya error posisi yang dominan pada sumbu Y saat navigasi dan pendaratan dalam simulasi , disarankan untuk melakukan tuning parameter kontroler PID internal PX4 lebih lanjut, khususnya pada sumbu Y, untuk meningkatkan akurasi dan mengurangi overshoot/steady-state error.
2) Evaluasi Jarak dan Keandalan Telemetri: Melakukan pengujian jangkauan (range test) dan keandalan koneksi radio telemetry dalam berbagai kondisi lingkungan untuk menentukan batas operasional komunikasi nirkabel antara GCS dan *Drone*.
3) Pengembangan Fitur Otonom Lanjutan: Mengembangkan fitur otonom yang lebih canggih pada ROS 2, seperti implementasi algoritma penghindaran rintangan (*obstacle avoidance*) atau pendaratan presisi (*precision landing*)

menggunakan *computer vision*, untuk meningkatkan keselamatan dan kemampuan operasi di lingkungan yang kompleks.

4) Uji Coba dengan Muatan Medis Aktual: Melakukan pengujian terbang dengan membawa muatan medis simulasi atau aktual (misalnya, sampel darah dalam packaging standar) untuk mengevaluasi pengaruh beban terhadap dinamika terbang, konsumsi daya, dan integritas muatan selama transportasi.

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LAMPIRAN

Lampiran 1 - Konfigurasi Pin ESP32

Mikrokontroler ini berfungsi sebagai unit yang menjalankana logika kontrol untuk menggerakkan motor servo, dan berkomunikasi dengan platform HTML melalui koneksi WiFi yang terintegrasi dengan webserver.

No.	Pin ESP32	Fungsi	Terhubung Ke
1	GPIO 13	Trigger Servo	Pin Servo (Signal)
2	3V3	Catu Daya Servo	Pin Power Servo (+)
3	GND	GND Servo	Pin GND Servo (-)

Lampiran 2 – Spesifikasi *Pixhawk* 6C

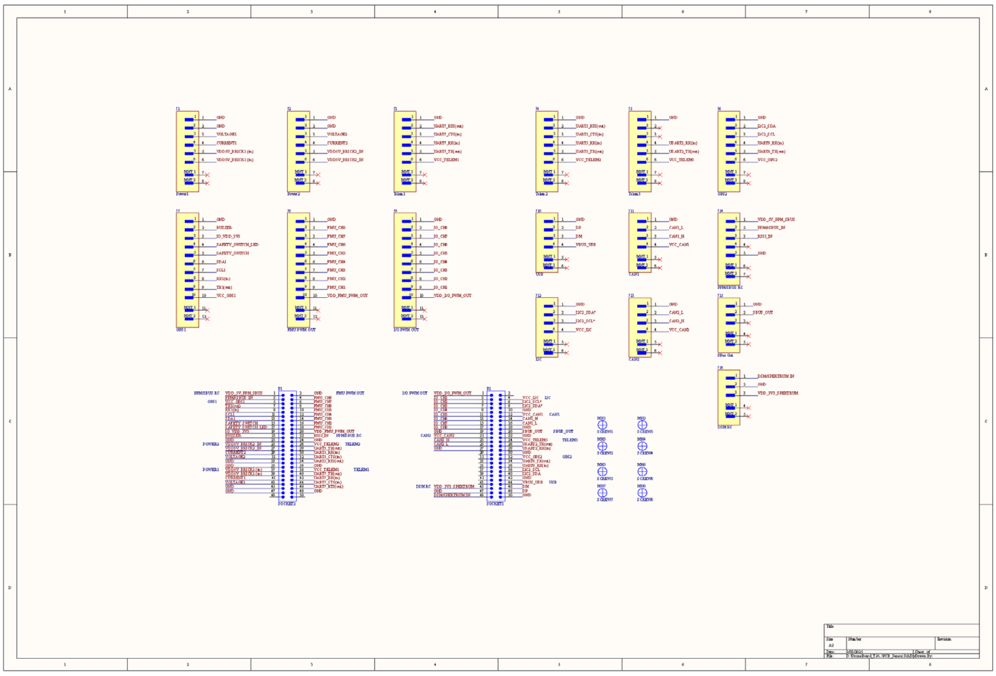
Pixhawk 6C ini berfungsi sebagai *flight controller* pada *Drone* dimana ini menjadi pusat kendali *Drone*. *Flight Controller* merupakan salah satu jenis *printed circuit Board* (PCB) yang ditanamkan mikrokontroler yang digunakan dalam teknologi *Drone* yang dapat menghubungkan berbagai komponen pada *Drone*.

Processor & Sensors	
FMU Processor	STM32H743, 32 Bit Arm® Cortex®-M7, 480MHz, 2MB memory, 1MB SRAM

Processor & Sensors	
IO Processor	STM32F103 32 Bit Arm® Cortex®-M3, 72MHz, 64KB SRAM
On-*Board* sensors	Accel/Gyro: ICM-42688-P
	Accel/Gyro: BMI055
	Mag: IST8310
	Barometer: MS5611
Electrical data	
Voltage Ratings:	Max input voltage: 6V
	USB Power Input: 4.75~5.25V
	Servo Rail Input: 0~36V
Current Ratings	TELEM1 Max output current limiter: 1.5A
	All other port combined output current limiter: 1.5A

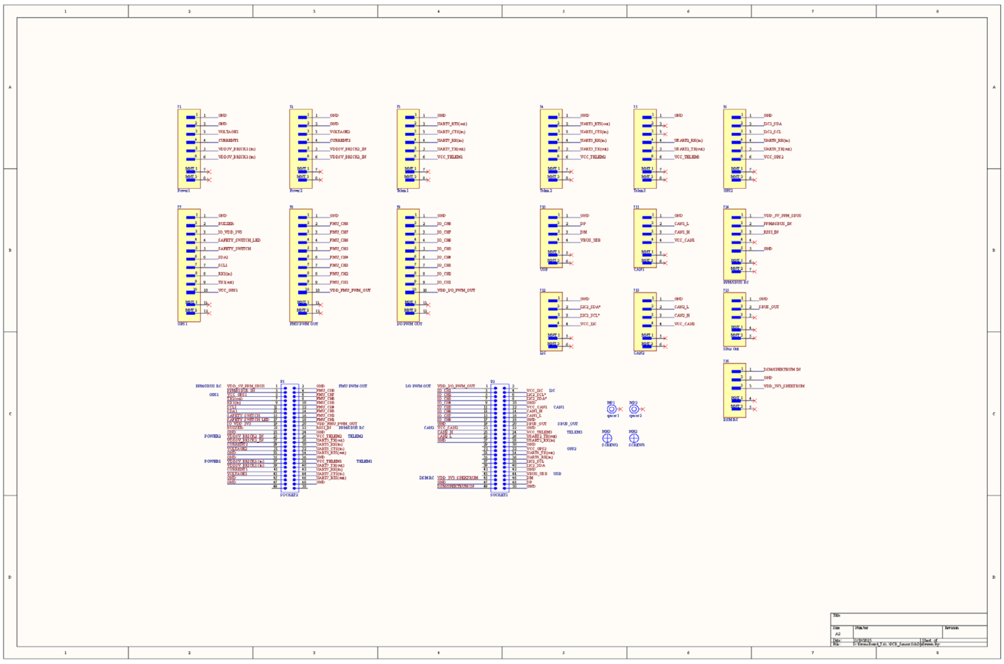
Lampiran 3 – Skematik Rangkaian *DroneBoard* - *Pixhawk*

Berikut merupakan rangkaian skematik *Drone Board* yang terhubung dengan *Pixhawk*.



Lampiran 4 – Skematik Rangkaian *DroneBoard* – Sensor

Berikut merupkan rangkaian skematik *DroneBoard* yang terhubung dengan sensor pada *Drone*.



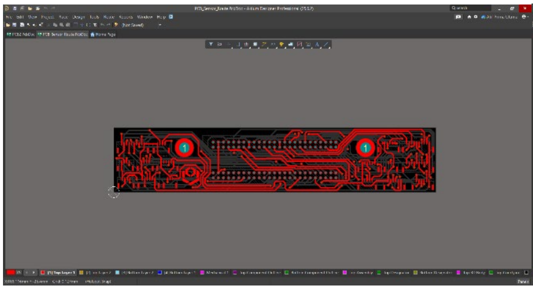
Lampiran 5 – Spesifikasi Servo

Servo berfungsi sebagai aktuator untuk mengatur sistem pengunci kotak medis pada *Drone*. Servo ini terhubung dengan mikrokontroler ESP32 dan dikendalikan melalui tombol *Toggle Lock* pada interface HTML dengan koneksi wifi.

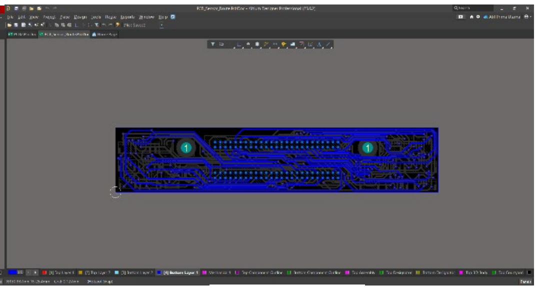
Control	Analog
Voltage	5V
Speed	60 degrees in 0.1s
Weight	9gram
Dimensions	23 x 12 x 29 mm / 0.9" x 0.5" x 1.1"

Lampiran 6 – Rangkaian jalur PCB *DroneBoard* – Sensor

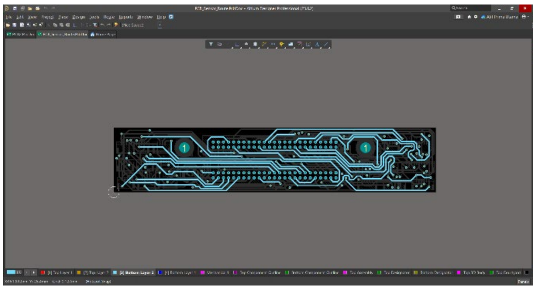
PCB *Drone Board* yang terhubung dengan sensor *Drone* memiliki dimensi 160x32 mm, dan dirancang dengan 4 susunan layer untuk mengoptimalkan dimensi PCB. Berikut merupakan rangkaian jalur PCB *Drone Board* yang terhubung dengan sensor pada *Drone*.



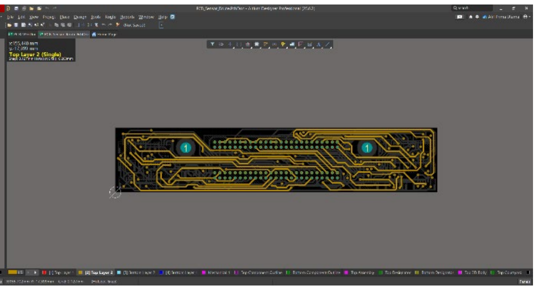
Layer 1



Layer 2



Layer 3



Layer 4