EMI Hardening of RPAS Incorporating Fly-By-Light

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Abstract - The implementation of fly-by-light technology within aircraft systems takes advantage of electromagnetic interference (EMI) immunity and various other benefits linking to weight reduction, increased speed, versatile bandwidths for data transfer, and improved survivability to temperature and humidity effects. These benefits allow for the development of remotely piloted aircraft systems (RPAS) to increase the system's capabilities and strengthen its survivability in the airspace. This report investigates the methods of transferring PWM signals through optical fiber cables to an RPAS servo motor and analyzes the potential effects of dispersion that may result in pulse width error. This includes the circuit design utilized for modeling the conversion of optical signals through a HFBR-1532Z transmitter to a HFBR-2533Z receiver, allowing for 88° movement in the servo motor at the output. Results through a 0.175 metre optical fiber cable show dispersion of 0.2165 ps/nm-km, which is further compared to a 50 metre optical fiber cable. The increased length of fiber contributed to a differential delay of 0.7 ps, representing a dispersion of 7.5x10^{-4} ps/nm-km. This project aims to further investigate the implementation of fly-by-light technology into an RPAS, rigorously testing the EMI susceptibility once fully developed and providing insight into the methods of increasing survivability in contested airspace.

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I. INTRODUCTION

Since the beginning of the study of optical fiber sensors, numerous ideas have been put forth and proposed applications have been developed. Although some types of optical fiber sensors have been commercialized to date, it is also true that only a small portion of the many techniques and applications that have been studied have been commercially successful. Nevertheless, optical fiber technology should be able to compete with other established technologies in many application fields [1]. These devices have several desirable qualities for sensing applications, including compact size, lightweight, simplicity of installation, low cost, and immunity to electromagnetic interference (EMI). Since they can measure changes in temperature, external refractive index, pressure, humidity, and electrical current in high-voltage environments, optical fiber sensors are incredibly versatile [2]. Understanding the link between optical fiber sensors and EMI is paramount for tackling difficulties presented in many application fields including aircraft such as remotely piloted aircraft systems (RPAS). The use of advanced electronic devices, particularly those used for communication, has led to a rapid increase in the use of electromagnetic waves in aircraft applications. Despite the advantages, electronic devices propose in the current world, the increase of electromagnetic waves associated with these devices poses a consequential threat to aircraft applications. All RPAS communications rely heavily on the mobile wireless network between them, whether they are direct communications between RPAS, or between RPAS and ground transmission stations [3]. The requirement for communications in aircraft such as RPAS creates risks and highlights the necessity for determining the construct of their respective architecture, especially in terms of flight control systems, and the methodology of transmitting and receiving communication signals.

A. Motivation

The motivation for the proposed fly-by-light project was to solidify the reliability of RPAS in the currently contested airspace. Although existing RPAS architecture is renowned for minimal energy consumption and effective energy efficiency, the implementation of hybrid power and communication systems [4], and fly-by-wire technology to operate these devices suffer in reliability and effectiveness in dominating the airspace. It is becoming increasingly relevant that EMI develops into a significant problem and is frequently an unwelcome phenomenon that affects the operation of electronic devices, particularly the communication capabilities of aircraft systems. The EMI phenomenon, which affects RPAS, is best prevented by shielding the radio-frequency band that is emitted by motors and power supplies [5]. As gigahertz communication technologies advance and environmental electromagnetic radiation intensify, it becomes more important than ever to increase the effectiveness of EMI shielding materials and systems [5]. The versatility introduced by fly-by-light technology [2] provides the mechanism of shielding required for the survivability of RPAS.

B. Project Scope

The role of fly-by-light implemented in RPAS as a factor to mitigate EMI has not been widely examined. The aim of this report is to investigate the existing difficulties of RPAS EMI susceptibility and to strengthen RPAS capabilities in the airspace through the implementation of fly-by-light. The influence of a range of factors on optical fiber cables in RPAS can be analyzed to examine if the EMI immunity of the system is effective in contributing to prolonged survivability in the airspace environment.

This report intends to answer the question: *To what extent has an RPAS EMI susceptibility improved by replacing copper wiring with optical fiber cable?* The accompanying secondary research questions with appropriate hypotheses are:

1) What are the common characteristics of fly-by-light designs in RPAS that are resulting in EMI hardening?
   H1. Optical fiber cables transmit signals through pulses of light; the signal integrity of these cables is optimized with immunity from electrical noise.
2) To what extremities of environmental interference can fly-by-light RPAS manage?
   H2. Fly-by-light RPAS builds on fly-by-wire technology for EMI susceptibility and aligns with some applicable military EMI requirement standards.

This project will focus on advancing current RPAS capabilities through the following outputs:

1) Simulating optical communication signal dispersion for optical fiber cable, including chromatic and modal dispersion.
2) Compensate for optical communication signal dispersion through circuit design.
3) Demonstrate conversion of PWM signal into an optical signal and back through circuit design.
4) Implement signal-by-light and power-by-wire into a static RPAS.
5) Design and implement signal-by-light and distributed power into a static RPAS.
6) Conduct flight testing of the RPAS for functionality purposes.
7) Propose a design for signal-by-light and power-by-light, based on the power requirements necessary.
8) Test the EMI susceptibility of the RPAS design and evaluate the performance to military standards.

This paper is structured to detail the following. In background information, the concept of EMI, specifically within the airspace, will be discussed alongside the purpose of RPAS and its emerging threats related to EMI. Following this is a systematic literature review outlining the existing applications of fly-by-light, its benefits of implementation, most noticeably EMI hardening, and how it relates to the aim of the proposed project. Once the research gap is understood, the proposed project's plan will be discussed, including the detail of deliverables to roadmap a strategic solution to the main research question, and potential difficulties involved in the process. The existing method to achieve success through research design and basic principles is discussed concisely, leading into the current project contributions produced. The simulations for modeling optical signals used within the design, and the electrical circuitry to enable such communications in a system are evaluated in length. These contributions will enable the ongoing work required to achieve the final project architecture, and the methodology in doing so will be explored.

C. Potential Extensions

The implementation of fly-by-light into RPAS has the potential to explore a complex variety of research areas in aircraft systems. Given that the project will consist of simulating data, designing circuitry, and testing the model under a variety of environmental conditions, the extent of continuous improvement and exploration in maximizing results is vast. The potential extensions to the project given the deliverables are achieved prior to the deadline include:

1) Widening the exploration into environmental factors on the RPAS design, including humidity, temperature, and pressure. This extension would simultaneously aim to contribute to EMI hardening whilst preventing environmental damage to the delicate properties of optical fiber components either from the environment and weather itself, or external weapon systems.
2) Investigating military standards of aircraft performance through precise testing at military facilities. The Air Warfare Centre (AWE) SQN Electromagnetic Test Facility at RAAF Base Edinburgh offers a vast scope of accreditation for testing methods [6]. This involves assessment of emissions and immunity - EMC emission standards - for conducted and radiated interference, and conducted and radiated susceptibility of electrical products that align with the MIL-STD-461 procedures (revisions of D, E, F, and G) [6]. Requirements for these procedures are also represented in MIL-STD-464C included in Appendix A.
3) Incorporation of weapon systems on the RPAS design, implementing effective measures that would maintain the EMI capabilities, and allow for system functionality with optical fiber cables.

II. Background Information

A. Electromagnetic Interference

Unwanted electrical signals are a type of electromagnetic noise or pollution that are produced and released by every power electronics equipment. The electromagnetic pollution could trigger other systems or equipment to function worse or experience electromagnetic interference (EMI) [7]. It has been understood since the early days of radio and telegraph communications that a spark gap, or conduction, produces electromagnetic waves with a rich spectrum of frequency components and that these waves can interfere with or disrupt the operation of a variety of electrical and electronic devices, including receivers and communications systems.

Free-space propagation is the method used by wireless communication data links, which makes them vulnerable to signal interference and disruption from a variety of sources. High frequency, very high frequency, microwave, and optical transmission frequencies are just a few of the electromagnetic spectrum frequencies that are used by wireless communication technologies [8]. At various portions or frequencies of the electromagnetic spectrum, interference and noise have different effects. Numerous other sources of electromagnetic emissions, including fluorescent lights, relays, DC electric motors, and lightning [9], produce electromagnetic waves with a wide range of spectral content that may interfere with various electronic devices, whether wireless or not.

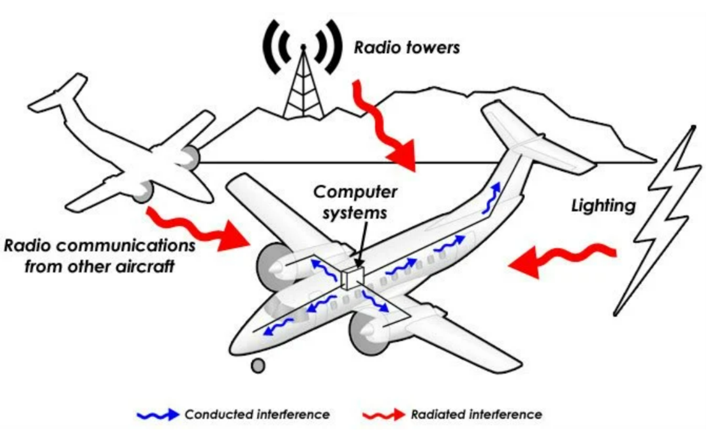

Fig. 1: External and Internal Interference Representation of an Aircraft System

Narrowing further into communication devices, the frequency bandwidths associated with devices like microwave (0.3-8 GHz) and radio frequencies (30-300 MHz), as well as frequencies from lightning strikes, and electromagnetic pulsates [10], are examples of EMI sources that have an impact on aircraft. Generally, a system such as an aircraft will experience conductive interference, or radiated interference as represented in Figure 1. Although this representation of interference types is simplistic, defining a technical list of EMI sources can facilitate formulation development of electromagnetic compatibility (EMC), where a system or device has the ability to operate within the presence of EMI. These sources include [10]:

- Incidental Interference
- Intentional Interference
- Environmental Interference
- External Noise
- Adjacent Channel Interference
- Band Congestion

The principle of limiting EMI susceptibility is also known as EMI hardening and can be used as a measure to increase the capabilities of RPAS to operate under the threat of counter-drone strategies.

B. Purpose for RPAS

RPAS, also known as "drones," are widely utilized in the military but also have a variety of non-military uses [11] in government, industry, commercial, and recreation. Technology advancements and ongoing regulatory developments will enable their use in domestic airspace [12]. Additionally, to the practical and financial advantages of a robust civil RPAS industry [13], the prospective advantages for the military RPAS industry are also generally acknowledged. As established, the variety of fields utilizing RPAS has extended its implementation into a multitude of functions.

As systems came together, there was a renewed push to investigate the potential of RPAS for national mapping [12] in greater detail contributing to the topographical maps and geographical information of countries. RPAS is without a doubt effective in supporting emergency and disaster management [14], including floods, earthquakes, bushfires, and hazardous material leakage due to their exceptional monitoring and detection capabilities. Applications led to effective use in agriculture to carry out specific tasks [15], such as studying weather conditions and variations, crop disease, and land fertility, and can cover nearly 10 to 15 times as much ground as conventional land-based methods [16]. In terms of medical reliability for improving daily living conditions, RPAS has been successfully used to deliver medical supplies, vaccines, and microbiological samples to rural and remote areas [17]. These applications of RPAS not only indicate its purpose and capabilities, but transparently outlines how the systems gained significant momentum in research, development, and popularity in various fields of military and non-military sectors [18].
Armed forces and rebel organizations have used remote-controlled aircraft for years to conduct reconnaissance, target infrastructure, and launch attacks on desired targets [19]. According to Shaikh [20], RPAS, missiles, and other weapons were heavily employed in the conflict between Armenia and Azerbaijan over the disputed regions. A wide range of traditional and strategic air and missile strikes and defense platforms were used during the 44-day conflict. Both reconnaissance missions to support the use of artillery and strike missions were carried out by RPAS of Russian, Turkish, Israeli, and domestic designs. T-72 tanks and sophisticated S-300 air defenses were among the heavy ground units that RPAS and loitering munition attacks were able to eliminate [20]. This real-world example of the implementation of RPAS in the current climate of conflict expands on the non-military applications of RPAS and leads into the reasoning behind the technology's countermeasures.

C. Counter-RPAS Strategies

As discussed in their purpose, RPAS pose emerging threats in contemporary conflict and have done so throughout their tremendous development. The rise of anti-drone systems in sensitive areas [21] has been improved to detect, localize, and defend against invading drones in order to mitigate these risks [22]. Countering RPAS is a challenging task due to the variety of technologies used in different systems, for different purposes. The performances of counter-RPAS technology and systems are limited by the unknown, yet multiple applications exist to target RPAS vulnerabilities. Not only can countermeasures be categorized into offensive and defensive applications, but they can also be sub-categorized into detection, tracking, evaluation, and interference [21] [23]. Radar surveillance is a promising technology specifically improved for accuracy purposes to effectively mitigate RPAS operations [21] [22]. Although detection and tracking are circumstantially effective, neutralization through intentional electromagnetic interference (IEMI) on sensors within RPAS applications has been deemed to be an optimal countermeasure [23]. By using high-power electromagnetic technology within the range of 100MHz and 3.4GHz frequencies, the immunity levels to qualify RPAS systems to electromagnetic standards are tested.

III. LITERATURE REVIEW

As described by [24], a systematic literature review is a thorough summary and critical analysis of relevant applications linking to a research topic. The intent of a systematic literature review is to inform the target audience of the current literature and form the basis for exploring future research in the area with minimized bias. To outline the research gap of the proposed project, an explicit and rigorous evaluation criterion was used throughout the systematic literature review in line with the typology discussed in [25], seen in Figure 2.

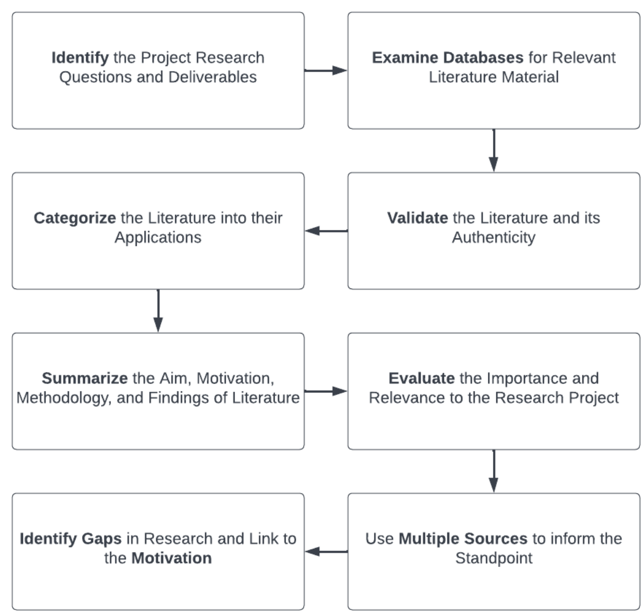

Fig. 2: Overview of the Literature Review Process to Outline Research Gaps

A. Search Procedure

The search process for peer-reviewed articles was conducted by filtering through databases accessible through the University of New South Wales (UNSW) Library collection, utilizing keyword selections and backward screening strategies [26]. The databases involved in this search process included IEEE Explore, SPIE Digital Library, Science Direct, Google Scholar, AIAA, and the NASA Technical Reports Server. Additional literature was selected through the citations within these articles; the search process was adapted from the effective analysis styles proposed in [27] [26].

B. Literature Selection

Inclusion criteria were utilized to maximize the quality of the review throughout [28]. The inclusion criteria for quality purposes were:

- Full-text articles including an abstract, introduction, and conclusion
- Article is written in English
- The article related to the research questions
- The article wasn't a duplicate from a different database
- The article was published in a journal or conference, or included in book chapters
- Results or findings produced a clear and concise outcome and/or progress

The literature applicable to the research questions was categorized into three main areas. These areas are the existing applications of fly-by-light, the benefits of fly-by-light, EMI hardening provided by fly-by-light, and the difficulties that currently exist for RPAS EMI susceptibility. For each piece of literature reviewed, the abstract and conclusion provided sufficient information on whether the piece met the inclusion criteria, and which area of review it was categorized within. The remaining process was completed as described in the flow chart in Figure2. The applications of fly-by-light established the fundamental projects that analyzed the implementation and progression of technology in aircraft.

C. Applications of Fly-By-Light

The YA-7D test aircraft was a noticeable project that implemented a complete fly-by-light flight control system in 1975 [29]. The Wright Research and Development Centre at the Wright-Patterson Air Force Base, Ohio, had demonstrated the digital tactical aircraft control (DIGITAC) program [30] and its use of fiber optic data buses to interconnect avionic equipment [31] through successful flight-testing. The results of the YA-7D aircraft were additionally analyzed by the Naval Electronics Laboratory Centre in California, presenting a wide range of successful demonstrations, concluding fiber optics as a feasible technology for signal interfaces on military platforms [32]. The reports outlined the project's optical fiber components, including the digital and analog receiver schematics, the analog transmitter schematic, the LED and photo-detectors, and the electro-optic circuit cards [33] which are all pertinent to the operation of an aircraft's optical fiber communications.

The 1980s saw significant developments in rotorcraft model-following technology thanks to Boeing's design and flight testing of the Advanced Digital/Optical Control System (ADOCS) under a US Army contract [34]. Due to sensitive penalties from new developing threats such as directed-energy weapons, the development of fly-by-light systems had strong technological and economical incentives in helicopters, which led to the design of the Sikorsky UH-60A Blackhawk helicopter, later known as the "Lighthawk" [35]. With the modified Black Hawk equipped with a digital "fly-by-light" system, the ADOCS program logged more than 500 hours of flight testing effectively providing solutions to developing threats to aircraft within the EMI realm [35] [36]. On-going research and design led to an airborne rotorcraft simulator launched at the German Aerospace Centre in Braunschweig with the objective to design an advanced test vehicle for the evolution of future control technologies [37]. The Active Control Technology Demonstrator and Flying Helicopter Simulator (ACT/FHS) produced a fly-by-light twin-engine helicopter, the Eurocopter EC-135, by replacing its flight control system [37] [38]. The validated flight models of the EC-135 formed the basis of DLR's new Flying Helicopter Simulator, which significantly refined evaluations of advanced helicopter control concepts and demonstrations of new technologies for future rotorcraft [39].

Within the 1990s, development programs for both military and transport aircraft took off as a race for complete fly-by-light systems. The NASA Dryden Flight Research Center (DFRC), California, became involved in fiber optics through the smart actuator program [40]. The primary goal of this program was to demonstrate local closed-loop control of a flight control surface actuator by incorporating miniaturized smart electronics into the actuator assembly of the F-18 [40] under the Fiber Optic Control Systems For Advanced Aircraft (FOCSI) program [41]. Additionally, the FOSCI program saw the exceptional design of electro-optic architecture, optical sensors, and interface control within the F-18 providing considerable knowledge in the construction and operation using fly-by-light applications [41] [42]. The goals of fly-by-light programs have evolved in tandem with the programs themselves, from open-loop monitoring of optical sensors in the Fiber Optic Control Systems Integration (FOCSI) program to in-flight demonstration of optical control in the Fly-By-Light Aircraft Closed-Loop Test (FACT) program [43]. The FACT program is a crucial link, which not only allowed for the in-flight fly-by-light demonstration on crucial flight control surfaces but also for the development of optical position sensors mounted internally in flight control actuators and the Electro-Optical Architecture (EOA) required to decode these sensors [43]. The Fly-by-Light Advanced Systems Hardware (FLASH) initiative utilizes both the hardware and lessons acquired from the FACT program. The FLASH program used a total system design methodology to create all the technologies needed to effectively solidify fly-by-light [44] into practice. FLASH addressed the requirements for the flight control computer and its interfaces to sensors, actuators [45], and cross-channel data links [46], as well as the system cable plant [47] [48], including interfaces to sensors, controls, and the engine [49] [50].

Back in the 1990s, the dual use of military and commercial aircraft industry was pushed towards increased standardization, modularization [51], and the use of flexible architectures and hardware that can be applied to multiple airframes [52]due to the high cost associated with the development and acquisition of new, highly complex, and integrated digital control and avionics systems. Simultaneous with the advancement of fly-by-light in military systems such as the FLASH program and other applications with the F-18, transport and airliners were researched and practically investigated [53]. A series of aircraft tests were carried out by the NASA Langley Research Center in 1995 with the goal of describing the electromagnetic environment inside and around a Boeing 757 airliner [54] [55]. The NASA Fly-By-Light/Fly-By-Wire Program provided funding for the initial phase, which was carried out in the LESLI Facility at the USAF Phillips Laboratory and involved on-the-ground electromagnetic measurements using the NASA Boeing 757 [56]. As the aircraft flew past RF transmitters that were known to exist, measurements were made of the electromagnetic energy coupled into the aircraft [54] and the signals induced on specific structures. These measurements were carried out in order to supply information for the verification of computational methods for the evaluation of electromagnetic effects in commercial transport aircraft [57]. The measurements carried out with the NASA B-757 were near Wallops Island's ASRF radar (430 MHz), a fixed transmitter powering an LP array (172 MHz), and a Voice of America station (-25 MHz) [56]. The FLOAT system made its first flight on a Boeing MD-90 on January 26, 1998, flying for the Douglas Products Division's Flight Test department [58]. For the MD-90 flight demonstration, the fly-by-light/power-by-wire distributed control system used by the FLOAT system replaced the mechanical aileron trim system's cable and pulley predecessor [59] [60]. Chai discusses a potential low-cost solution to commercial aviation in [61] regarding the SWII-13 aircraft testing procedures and respective results. The aircraft implemented fly-by-light technology to investigate structural weight, drag, and bandwidth characteristics for more economical flight [61].

Navigating through the airspace whilst being lighter than air was a desirable characteristic of aircraft fulfilled with the application of airships [62]. Building helium-filled and hot-air airships involved numerous companies throughout the 20th century [63]. The Skyship 600 took flight for the first time on October 23, 1988, entirely under the control of the fly-by-light control system, marking another aviation first for Airship Industries as a result of the field's evolving technology [62] [63]. Over the course of 150 hours of flight testing, it significantly reduced the physical workload of the pilot and enabled the surfaces to deflect fully during the entire range of the airship's manoeuvres, greatly improving control [63]. The optical fiber connectors presented issues at various stages of the project. Direct operating costs were found to decrease by a factor of four for fixed-wing aircraft and a factor of five for helicopter designs [62]. The development of fly-by-light airships continued through to the 1990s with the challenges faced by the U.S Navy in testing the YEZ-2A [64]. The YEZ-2A design had elements not found in earlier airships and was technologically very sophisticated. The YEZ-2A was designed for extended at-sea deployments of previously unprecedented length, with the need for underway replenishment [64]. Since the last Navy airship tests were conducted thirty years ago, testing and evaluation standards have greatly improved. The combination of these three elements significantly increased the difficulty of testing and evaluating the YEZ-2A [65] [64]. The fly-by-light system was demonstrated to reduce the physical workload for the pilot, allowing the crew to fly longer missions without becoming overly exhausted [65].

D. Benefits of Fly-By-Light

The YA-7D test aircraft was one of the first aircraft applications to successfully demonstrate the benefits of fly-by-light technology [33]. The A-7 optical fiber components could effectively operate in a military aircraft environment [30]. Economic analysis shows that optical fiber technology clearly offers significant future benefits [32] in terms of reduced system weight, survivability, improved reliability, increased data transmission, and use of maintenance at reduced life-cycle costs while meeting or exceeding the requirements of EMI in comparison to conventional-wire systems [31]. It was discovered that the optical fiber interface system was simpler to maintain and troubleshoot than the wire-interface system [30].

The foundation of fly-by-light benefits provided by the A-7 was confirmed by other applications and investigated additional findings. According to studies by the US Air Force, optical fibers made it possible to implement power-by-wire (PBW) technology, which resulted in 10% reliability, 14% vulnerability, and 12% maintainability improvements [49] as well as a 20% reduction in operational support transport aircraft load, and a 15% reduction in manpower requirements [44]. Studies show that by detecting control system failures in real-time, a method utilising optical fibres and neural networks can significantly lower the maintenance cost of control systems [49] [66] [67]. Carlos summarised in [68] that future aircraft developments must be more cost-effective, which calls for optical fibres.

The benefits to mission performance brought on by the technological advancements and objectives of NASA's Phase II High-speed Research (HSR) Program have been evaluated on a first-order basis [69]. The synthetic vision was estimated to save 1.3% in take-off gross weight (TOGW) while the development of the fly-by-light system was estimated to save 2.7%, for a combined flight-deck system's prorated benefit of 4% TOGW or 9% of the overall benefit from Phase II [69]. It should be noted that a significant portion of flight-deck development enhanced vehicle safety, and made cross-disciplinary benefits that enhanced engine performance and decreased structural weight [70]. Additionally, communication links greatly streamlined system integration on the F-18 [40], minimizing installation time and cable harness weight. Furthermore, the task of designing and integrating an optical fiber actuator into the F-18 decreased size and weight while enhancing performance and reliability [41].

Wider bandwidth communication is a benefit of using optical fiber buses and interfaces to provide a distributed fly-by-light architecture [42]. Due to its capable 20 Megabits per second data transmission, the optical fiber data bus AS1773 outperformed its fly-by-wire counterpart MIL-STD1553B, according to FLASH Task 2B [46]. Additionally, data latency was minimized and undetectable by the Engineering Test Pilot by increasing the processing iteration rate of distributed components, such as the fly-by-light Cockpit Interface Terminals [46]. Carlos concluded his findings in [44] that future aircraft will be able to meet higher data rates and volume needs attributable to optical fibers, which offers the high bandwidth required for standardized testing [71]. The Airbus A380, Boeing 787, and many other aircraft use the optical fiber avionics bus specification known as Avionics Full-Duplex Switched Ethernet (AFDX) [55], which is described in Aeronautical Radio INC (ARINC) 664 Aircraft Data Network. According to the test results, AFDX networks can transmit 100 to 200 times more data than an A429 link, with a raw bit rate of 100 Mbits/s compared to 1 Mbits/s for 1553 and 100 kbits/s for ARINC 429 [55]. A Primary Flight Control Computer's (PFCC) internal optical fiber transmission implementation was evaluated as part of Honeywell's contribution to Task 2A of the FLASH program [72]. These optical media components' capabilities under the typical temperature, vibration, and humidity stresses experienced by aircraft were assessed. Over every environmental stress, there were only very slight variations in functionality. According to Stange's research covered in [73], there was no damage or long-term effects caused by environmental stresses. Individual applications and programs improving aircraft provide their own insight into the benefits of fly-by-light, however, the discussion of EMI immunity is a common characteristic involved across the range of literature investigated.

E. EMI Hardening of Aircraft

The EME in which aircraft must operate is becoming more intense due to the spread of high-intensity emitting sources on a global scale and the increase in electric aircraft [74]. The radiated susceptibility requirement documents derived from military standards, serve as the source for improving EMI susceptibility [75] in aircraft systems. A basic design flow map of the EMI hardening design of a system is provided in Figure 3.

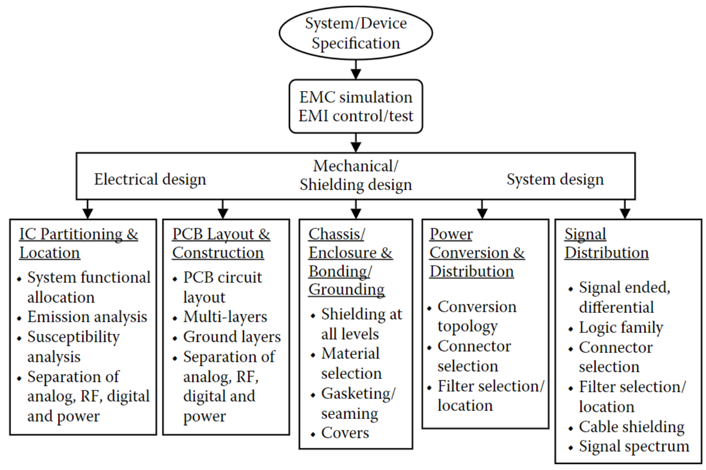

Fig. 3: Flow Diagram of Generic EMC Design Principles Outlining Electrical, Mechanical and System Design Techniques

A number of standard methods and variations on standard methods are used to measure the effectiveness of shielding in an enclosure, conductive gasket, or other EMI shielding components. However, because the standardized methods require well-defined samples, which are occasionally impossible to create because of the characteristics of the object samples to be measured, they cannot always be used. To measure specific gaskets or other shielding materials with a specific shape and size, it is frequently necessary to design custom measurement equipment based on industry standards [74]. NASA Dryden Flight Research Centre investigated the rigorous testing of EMI susceptibility in the F/A-18 aircraft. Vibration, altitude, and temperature have little effect on the McDonnell Douglas F/A-18 assembly [40]. The sensor and cables are compact and inherently immune to EMI due to the absence of electric or magnetic components. All parts were military-qualified to 883B specifications and incorporate EMI shielding techniques [76], even though the need for EMI shielding and surge quenching circuits are eliminated [42]. A large volume of fly-by-light studies have demonstrated that to lessen EMI interference, fiber optic data links [71] can be installed in place of fly-by-wire on many dual-purpose aircraft [77]. High-speed optical fiber links support high data rates while reducing EMI issues that are frequently present in fly-by-wire alternatives [57]. For lengthy data transfers, optical fiber data links and buses replace the need for specialized EMI shielding [74] [71]. Task 1 of the FLASH program successfully showed how cable plants can provide extremely fast interconnections that are EMI immune [47] for use with mission avionics and advanced vehicle management systems [48]. Bedoya investigated EMI testing of aircraft aligning with MIL-STD461 requirements in [44], specifically the addition of a new requirement of 200 Volts per meter from 10 KHz to 40 GHz. The findings of the FLASH, FACT, and A-7 results are prime examples proving the immunity of fly-by-light technology to EMI [66] [43] [32].

Finnell states in [78] that multi-functional advanced window coatings are required for drone applications. An anti-reflective film, an EMI layer, a solar filter that rejects unwanted spectra, and a hydrophobic outer coating are all common features of windows [78]. By including multi-functional features in the outer window, sensor performance can be significantly improved. It is possible to add hydrophobic coatings with little to no effect on transmission through the visible and near-infrared spectrum. Similar research from Fredell in [79] suggests for RPAS windows and optics to withstand a variety of environmental threats, a modular design approach is presented. With the addition of thin film heaters, hydrophobic coatings, and surface treatments, as well as transparent conductive layers to shield against electromagnetic interference, window performance of RPAS can be improved.

IV. Planning

A. Project Plan

The project's deliverables and a summary report are expected to be completed by 24 Jun 2023 and submitted through UNSW Canberra. The remainder of the project's timeline is represented in Appendix B compiling of the tasks to be completed, with their appropriate start and end dates. The approach taken for completing this project was to interrelate the timing of tasks to be completed to allow for a consistent flow of work and to lead the previous task and possible implications into the next field of work. The majority of the design and simulation of practical applications in this project will be completed by 21 Oct 2022 and the results will be outlined in this report. The outcomes of these design tasks and simulations will be implemented into the practical system to evaluate and improve consistently over the practical testing phase in 2023.

The cycle for the practical testing phase will see the project architecture under consistent flight and redesign from results to enhance the success of EMI testing further on. This cycle will prepare the architecture for potential extensions outlined, most noticeably visiting the AWE test facility for a vast range of accurate and accredited procedures. The EMI testing process will see significant benefits in this project's design and allow for optimal research into the improvement of RPAS EMI hardening. Furthermore, the ongoing review of literature on the background subjects will allow for adequate subject matter knowledge regarding the merging of multiple broad areas of research. This is important for further potential research in the field of improving RPAS EMI capability, as well as providing expert-level understanding when delivering presentations and updates on the project. It is pertinent to the efficiency of the project quality that the following questions are answered as the timeline progresses to each task outlined in Appendix B:

1) Are the research questions being addressed in this task?
2) What methods of this task are addressing these questions?
3) Is the data or results acquired accurate, reliable, and relevant in achieving the aim of the project?
4) What could be done further in this task to explore potential research in this field?

The materials used for the project can be planned appropriately, however, knowledge of potential required materials with the current progression is limited and will be detailed throughout the remaining timeline. The current list of planned materials to use is listed below:

- Ready-to-fly (RTF) RC - remote control airplanes - with frequency-hopping spread spectrum (FHSS) 2.4GHz receivers and controllers, and servomotors
- HFBR-R/EXXYYYZ series plastic optical fiber cables in black polyethylene jackets, including transmitters and receivers.
- PCBs for circuit implementation
- Analog Discovery 2 USB oscilloscope and instrumentation system for design and testing purposes
- UNSW Electromagnetic Environmental Effects (E3) testing room with signal generators and amplifiers.

The majority of the budget for this project will be direct costs associated with the purchase of the RPAS models. To avoid potential issues with resource gaps, three to four airplanes will be purchased, which are averaged at $200 AUD each. The indirect costs involved in this project will be for potential travel purposes and research at external testing facilities to the UNSW Canberra campus and are subject to change. Overall, the estimated budget for this project is between $600 to $1,100 AUD in total.

B. Potential Difficulties

A practical research project can be challenging for the requirements to understand the knowledge required, simulate applications, design applications, and undergo precise practical testing. Due to the extent of project requirements, the RPAS fly-by-light system may experience potential difficulties in the project process, some are detailed in Appendix B. The potential difficulties of the project include:

1) Time constraints meeting deadlines of tasks, including issues with flight testing or damages requiring additional ordering of resources
2) Risk factor of ineffective EMI testing methods with equipment available due to limitations.
3) Having concise subject matter knowledge in all areas of research (RPAS and their functionality, optical fiber applications, EMI including MIL-STD revisions real-world applications) when presenting or discussing results, due to the complexity and volume of knowledge required
4) compatibility issues with optical fiber cables and RPAS components

Although situational difficulties may arise in the future, being aware of the potential difficulties early allows for methods to be implemented to avoid issues throughout the project. These methods include:

1) Interrelating tasks to allow for insight and prevents backtracking progress that may impact time availability. Additionally, setting realistic timelines in the project planner will provide adequate time availability based on recommendations given by subject matter experts and individual research performed
2) To reduce the risk of limiting EMI testing equipment, organizing alternative solutions for EMI testing will allow for options, including the availability of the AWE test facility which is currently underway
3) Having concise subject matter knowledge in all areas of research (RPAS and their functionality, optical fiber applications, EMI including MIL-STD revisions real-world applications) when presenting or discussing results, due to the complexity and volume of knowledge required. As described in the project plan, the ongoing literature review will assist in understanding the knowledge to certain degrees of depth, which will be improved further whilst simultaneously exploring the practical applications of the project
4) For compatibility issues with components, precise research can prevent the majority of these issues from occurring, however, physical testing during design tasks will allow for more accurate findings regardless

Although on a larger scale, Harris provides insightful recommendations [55] for the implementation of optical fibers in aircraft, which is informative for countering potential technological difficulties with optical fiber cables in this project.

V. Methodology

A. Research Design

This report has detailed the background information of EMI, the purpose of RPAS in the modernized world, and most importantly the EMI hardening of RPAS. These concepts merge into a formulation to address the main research question, 'To what extent has an RPAS EMI susceptibility improved by replacing copper wiring with optical fiber cable?' with support of simplified deliverables to produce a solution.

The tested models of the RPAS designs in this project are derived from a detailed simulation, analyzing optical fiber cables and the production of expected communication signals. The analysis of the optical fiber cable through simulation depicts any required compensation for the resulting modal and chromatic dispersion of signals through transmission. Compensation for these dispersions and the conversion of pulse-width modulated (PWM) signals in optical fiber cables are typically modeled by circuit devices for these power applications and a block diagram of this process is included in Figure 4. Power-by-light and signal-by-light designs can be modeled in RPAS with discrete properties allowing for effective fly-by-light technology, and functionality of the architecture

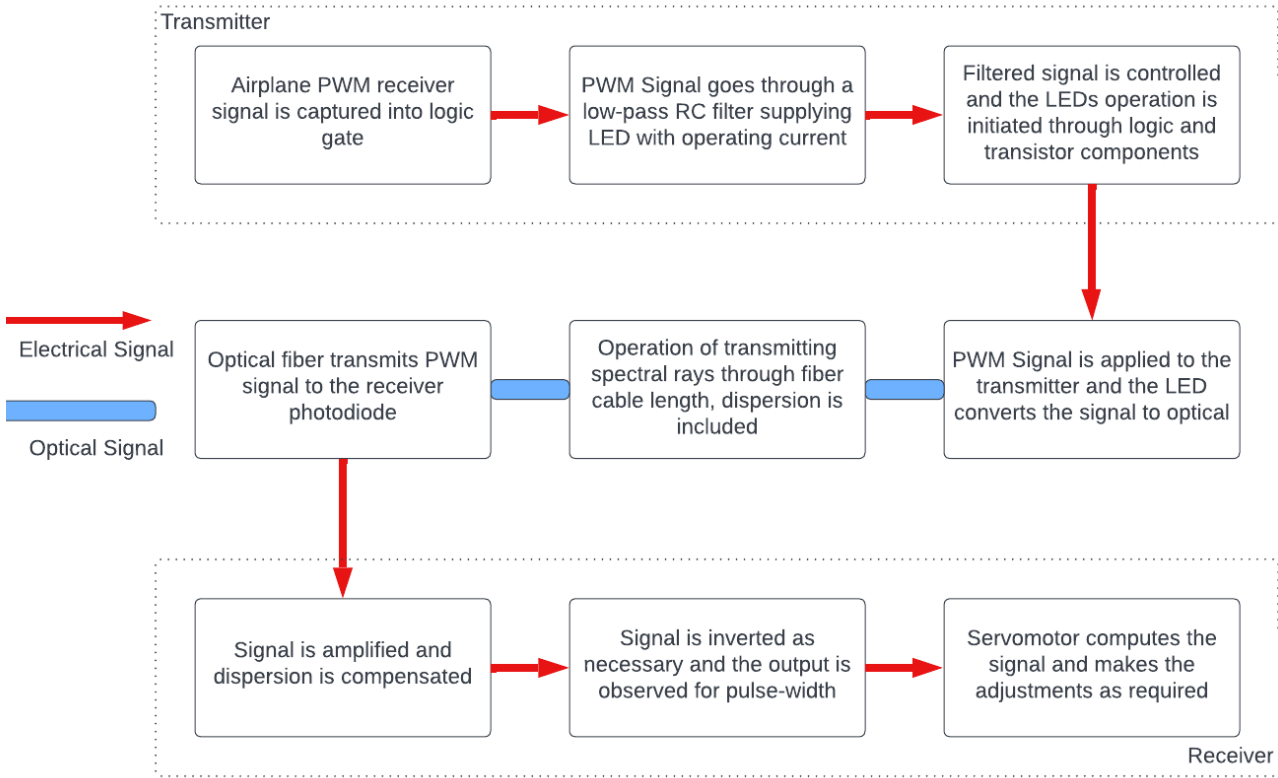

Fig. 4: Block Diagram of Circuit Process - Airplane Receiver to Servomotor - Capturing Results

examined through vigorous flight testing. Once effectively functional, a series of radio frequencies emitted by a service of equipment can target such a device, and observations for its survivability can be analyzed in great detail outlining its strengths, limitations, and most noticeably its operation. Further realization of fly-by-light RPAS survivability will dictate the future research required and progression toward state-of-the-art technology in this limited field of results.

B. Background Theory and Analysis

LEDs have a spectral shape that is approximately Gaussian and are moderately narrowband emitters. The peak wavelength, which is the wavelength of the peak of the spectral density curve, is the most typical spectrum-based description [80]. The Gaussian function used to approximate phosphor emission is defined [81] as:

$$S(\lambda, \lambda_c) = I \cdot e^{-(\lambda-\lambda_c)^2/\tau_o^2} \tag{1}$$

Where S is the relative spectral intensity, I is the intensity scaling factor, λ is the wavelengths, λ_c is the peak wavelength, and τ_o is the spectral width, otherwise known as the full width at half maximum (FWHM) [81].

The time delay between two spectral components is separated by a frequency interval denoted by the dispersion coefficient [82] given by:

$$D = -\frac{2\pi c}{\lambda^2} \cdot \beta_2 \tag{2}$$

Where c is the speed of light, λ = 2πc / ω is the carrier wavelength, and β_2 is the group velocity dispersion (GVD); the dispersion coefficient is measured in ps/nm-km [82]. Furthermore, intermodal dispersion caused by these time delays has consequential effects on the broadening of the spectral pulses. Thus, calculating the output pulse width of the fiber is essential in modeling and is found as:

$$\sigma = \frac{n_1 L \Delta}{\sqrt{12} c} \tag{3}$$

Where L is the length of the fiber, and Δ is the relative index difference.

The propagation distance after the input pulse is broadened is known as the dispersion length describing the dispersive effects of a medium, and is derived [83] to be:

$$L_D = -\frac{\tau_o^2}{|\beta_2|} \tag{4}$$

Chromatic dispersion, also referred to as wavelength dispersion, is an indicator of how much the effective propagation velocity varies with wavelength depicted in Figure 5. It is made up of two factors: waveguide dispersion, the ratio of velocity change to wavelength change, and material dispersion, the change in the glass's refractive index with wavelength [84].

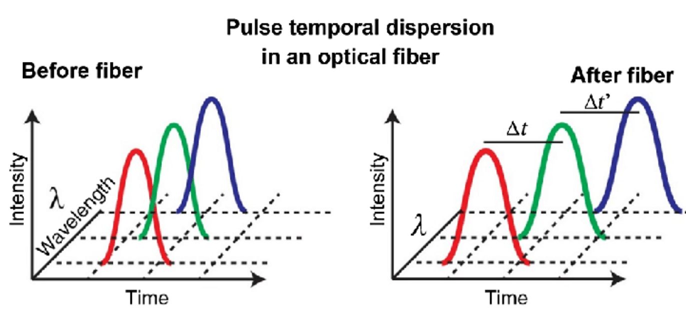

Fig. 5: Chromatic Dispersion of an Optical Fiber Cable through Spectral Separation

The total dispersion coefficient is given by the following [83]:

$$D = D_m + D_w \tag{5}$$

The material dispersion is given [83] by:

$$D_m = -\frac{\lambda_o}{c} \cdot \frac{d^2 n}{d\lambda_o^2} \tag{6}$$

Where λ_o is the free space wavelength, and n is the refractive index of the material. The waveguide dispersion for a step-index fiber, a fiber with the core's refractive index larger than the cladding's refractive index, is modelled [83] [84] as:

$$D_w = -\frac{n - n_2}{c\lambda} \cdot \left(\frac{V d^2(bV)}{dV^2}\right) \tag{7}$$

Where n_2 is the refractive index of the cladding, b is the normalized propagation constant, and V is the normalized waveguide parameter [83]. The critical angle of a step-index fiber can be calculated. The launching angle of rays within the fiber must be less than this angle to remain in the medium [85] and is derived as:

$$\theta_c = cos^{-1}\left(\frac{n_2}{n_1}\right) \tag{8}$$

The link to the critical angle and the acceptance angle is derived from Snells Law:

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{9}$$

The Numerical Aperture (NA) represents the optical power carried by a step-index fiber [85] and is calculated as:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{10}$$

The rise time and fall time of an LED are used to accurately represent its operation. These times are represented between 10% and 90% of the LED steady-state value [86]. For a low-pass RC circuit, the time constant, τ, is proportional to the rise time and can be approximated as:

$$\tau_r = \tau_{0.9} - \tau_{0.1} = \tau ln9 = 2.197\tau \tag{11}$$

Optical fiber communication involves the conversion of electrical signals to optical signals implementing a controlled and filtered pulse to be received and converted back to an electrical signal. The block diagram of the conversion process of a PWM signal through an optical fiber cable is included in Figure 4. A PWM signal from the controller is received by the optical fiber transmitter LED through controlled circuit components to achieve the desired operation. The LED transmits the signal optically to the photodiode in the optical fiber receiver which is amplified and converted back to an electrical signal. The signal is compensated through circuit design and received at the servomotor to regulate the airplane's engine speed.

$$time_{,1^\circ} = (time_{,180^\circ} - time_{,0^\circ} \,/\, 180\mu s) \tag{12}$$

The time for a degree of movement produced in the servo motor is calculated using Equation 12 [87].

VI. Current Progress

A. Simulations Modelling Signal Dispersion

The simulation of the optical fiber cable was performed initially to understand the expected response from the communication signals and to compute the required circuit components [88]. The Versatile Link series is a practical low-cost set of optical fiber link components. The HFBR-1532Z transmitter was analyzed on the Link series datasheet and the following characteristics [89] of the component were gathered for simulation purposes:

- The optical power ranges from -17.8 dBm minimum to -4.1 dBm maximum
- The peak emission wavelength is typically 660 nm
- Typical forward voltage of 1.67 V, and LED operating current of 60 mA
- Rise time of 80 ns between 10% and 90%, and fall time of 40 ns
- Numerical Aperture of 0.5

The HFBR-2533Z receiver was also analyzed on the datasheet [89] to compile its characteristics listed as:

- Input optical power (logic 0) is -13.3 dBm, and optical power (logic 1) is -53 dBm
- The output low-level voltage is 0.4 V, and the output high-level voltage is 2.4 V
- Maximum supply voltage of 7 V, the maximum output voltage of 7 V.
- Rise time of 80 ns between 10% and 90%, and fall time of 40 ns
- Numerical Aperture of 0.5

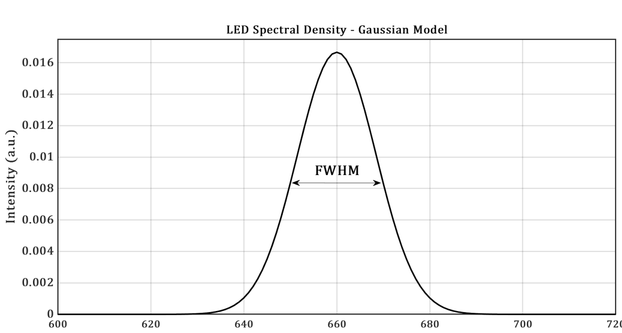

Fig. 6: Simulated Gaussian Pulse - Spectral Density - With FWHM

The first step was to convert the maximum output power from dBm to watts. The output power was found to be 0.3548 mW. A typical spectral width for a plastic optical fiber cable is 20 nm [90] which sets the maximum and minimum wavelength limits for the Gaussian model included in Figure 6. The intensities for each wavelength within the spectral density were calculated peaking at 0.0167 a.u. A PWM signal was developed for a time period of 3 ns modeling the receiver signal for the airplane controller used as the input signal to model the dispersion of the optical components. This signal was multiplied by the intensity values of each wavelength represented in Figure 6 to acquire the transmitted signal emitted by the LED. The appropriate rise and fall times of the signal were produced simultaneously by incorporating equation 11. The chromatic dispersion of this received signal through the simulated 100 metre optical fiber cable was plotted against time showing a delay of 0.0005 ns from the turn-on time to reach the steady-state power value, presented in Figure 7. Thus, the chromatic dispersion is expressed as 15.15 ps/nm-km at the output signal for a 100 metre cable. The reasoning behind the length was to represent a logical dispersion, as short lengths depict a negligible dispersion.

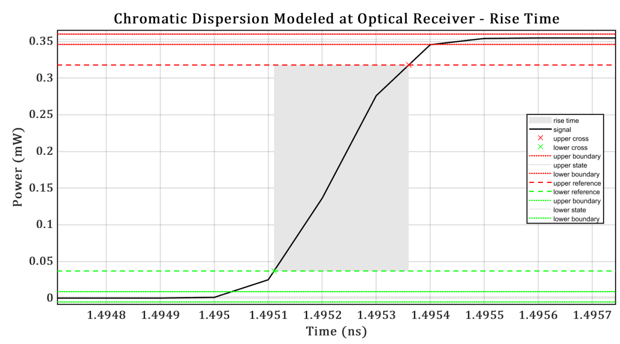

Fig. 7: Simulated Chromatic Dispersion at the Receiver of the Optical Fiber Cable for Rising Time, Between 10% and 90% of the Steady-State Power

The refractive indexes for each wavelength in the spectral density were calculated using the parameters supplied in [91], which was used to calculate the velocity of each wavelength through the optical fiber cable respective to the speed of light [92]. The refracted angle at the air/core interface was calculated using Equation 9 giving an angle of 19.5° [92]. The acceptance angle for this fiber using its NA and refractive index of the core was calculated as 39° [91] [92]. The intermodal dispersion was then simulated for the optical fiber cable at 100 metres using the resulting refractive indexes and acceptance angle. A representation of the intermodal dispersion is included in Figure 8, showing a delay time of 0.021 ns between turn-on time and steady-state power. The intermodal dispersion is expressed as 31.8 ps/nm-km through the process of receiving the PWM signal over 100 metres. The intermodal dispersion represents the time delay between wavelengths to project through the cable. The longer waves with higher wavelengths such as red light are observed first, whilst the shorter waves with lower wavelengths like blue or violet light are observed near the steady-state power with maximal delay through the cable.

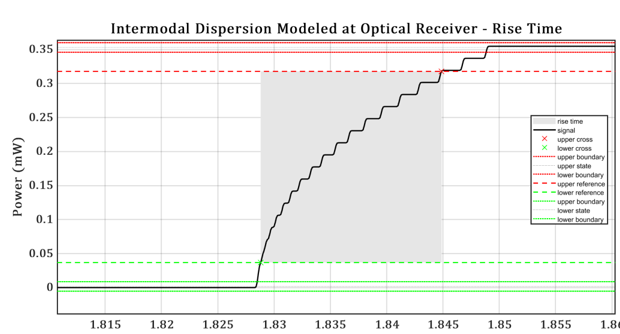

Fig. 8: Simulated Intermodal Dispersion at the Receiver of the Optical Fiber Cable for Rising Time, Between 10% and 90% of the Steady-State Power

The same process was modeled with various lengths of the optical fiber cable. Most noticeably, 0.175 metre cable length was simulated for the purpose of the PWM conversion testing, and the delay was found to be 0.0001 ns depicted in Appendix C. The dispersion was calculated from this time

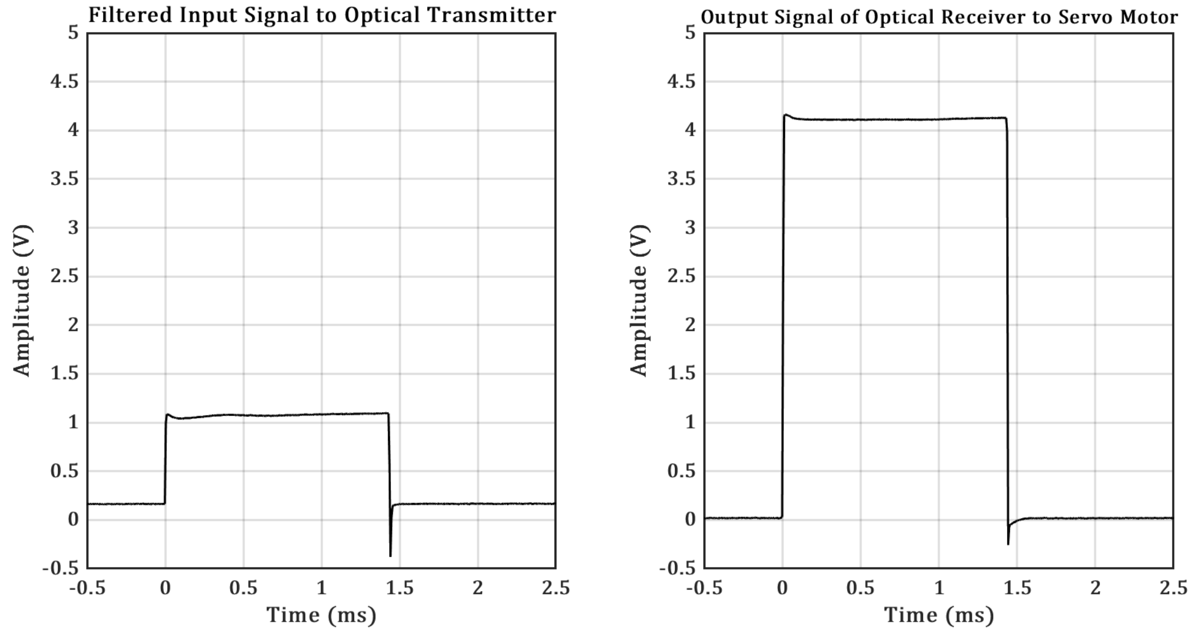

Fig. 9: Comparison of Filtered Input PWM Signal through the Optical Transmitter vs Output Signal of Optical Receiver to Servo Motor with Circuit Compensation

delay and expressed as 8.65x10^{-4} ps/km-nm. This finding will allow for comparisons between simulation and practical results. Observations of significant changes in dispersion at 1 km and above were seen which would result in the requirement for circuit compensation. However, due to the delimitations of the project, the research on the length is focused between 0 to 100 metres where the dispersion was calculated at a reasonable value.

B. Circuit Compensation for Signal Dispersion

Due to the simulation findings of the dispersion through the optical fiber cable, the requirement of circuit compensation to limit the dispersion is not necessary. The reasoning behind simulating the dispersion was to investigate the effects on the pulse width at the output signal of the receiver and compare this to the pulse width required for the movement of a servo motor. For a standard analog servo, the pulse width requires 10 μs before movement can occur [87]. Using Equation 12, the time for each degree of movement was calculated as 5.5 μs. Therefore the servo equates to 1.8° for 10 μs [87]. The dispersion simulated does not contribute enough pulse width change for the optical cable output which results in no concern for movement error of the servo motor. However, the signal received through the HFBR-2533Z component will be inverted [89] as represented in Appendix F. The compensation for this output was to implement an inverter through a logic gate. The logic gate used for this design is the MC74HC132A Quad 2-Input NAND Gate [93] due its high noise immunity characteristic and versatile drive capability. The circuit compensation is added at the output of the transferred optical signal received by the optical receiver.

C. Conversion of PWM Signals

The demonstration for conversion of the electric PWM signal into an optical signal and back was conducted through various theoretical circuit designs and practical testing. The RC receiver's PWM signal was first analyzed through an Analog Discovery 2 to monitor the input signal to the optical transmitter measured with a pulse width of 1.5 ms, and an amplitude of 2.77 V with 5 V input. The signal from this receiver is included in Appendix D. The initial design phase consisted of setting the parameters for the transmitter and receiver side of the optical fiber cable. The typical interface circuit is included in Appendix E. The resistor value was selected at 55 Ω to allow the photodiode to operate under 60 mA with a typical forward voltage of 1.67 V. The optical fiber cable was measured at 0.175 metres. No compensation at the output resulted in an inverted signal depicted in Appendix F. The signal was measured at the receiver output through the compensating inverter to achieve a PWM signal with a minor overshoot when turned on. The comparison of the input and output PWM signals is included in Figure 9. Additional testing was performed with the circuit attached to two servo motors, one operating directly from the input power supply, and the other remaining at the output of the optical fiber cable. The servo motor connected to the input of the optical transmitter was adjusted using the controller. The signal was analyzed to fluctuate in pulse width rotating the servo motor appropriately. The comparison of the minimum and maximum pulse width fluctuation is represented in Figure 10. The importance of the pulse width is the resulting degree rotation of the servo motor which is used for flight control of the aircraft. The minimum output had a pulse width of 1.007 ms, and the max pulse width was measured at 1.887 ms. The difference in these widths was concluded as 0.880 ms, converting to a total of 88° movement in the servo motor [87] between the minimum and maximum pulse width.

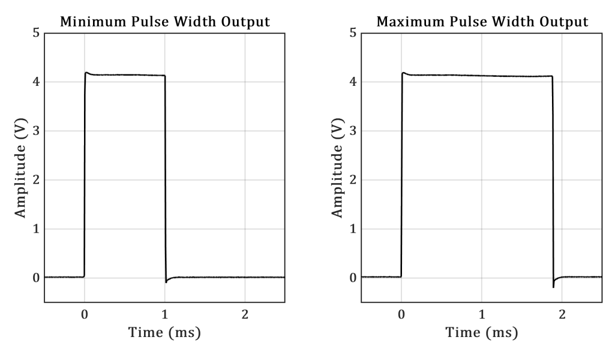

Fig. 10: Minimum Pulse Width Output Signal vs Maximimum Pulse Width Output Signal - Through RC Controller Movement

The optical fiber cable was increased from 0.175 metres to 50 metres to investigate the effects of dispersion when sending PWM signals to the servo motor. The input and output signal investigating this comparison is included in Appendix G. Furthermore, analyzing the dispersion effect between the 0.175 metre cable and the 50 metre cable was successful by comparing the output signals of each cable, and measuring the difference in pulse width to detect if an error would occur with the servo motor. The rise time dispersion was closely examined for each cable length represented in Figure 11. The pulse width had a difference of 0.00007 μs when increasing the cable length from 0.175 metres to 50 metres. The dispersion for the 0.175 metre optical cable was calculated as 0.2165 ps/nm-km through the transmission process. The differential delay from the increased cable length resulted in a dispersion of 7.5x10^{-4} ps/nm-km. When referring to chromatic dispersion, the simulated model in 7 represents this type of dispersion which is relative to the material when the cable length is increased. The result is negligible due to the required pulse width for servo movement in degrees [87], however, the increase of cable length does contribute to dispersion, which could result in complications when using higher lengths of cable up to kilometres [83]; this complication is not necessary to explore due to the project design, the effect is simply considered.

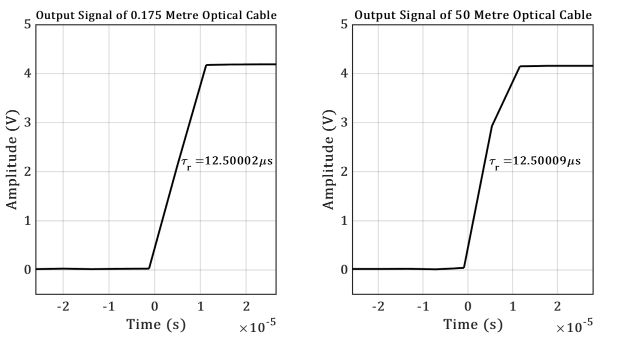

Fig. 11: Output Signal Rise Time through 0.175 Metre Optical Fiber Cable Compared to Output Signal Rise Time through 50 Metre Optical Fiber Cable Investigating the Effects of Dispersion Respective of Cable Length

The remainder of the analysis conducted for the 50 metre cable is represented in Appendix H. Most noticeably, the pulse width fluctuation for the 50 metre cable was analyzed to have the same overall movement for the servo motor of 88°.

VII. Future Work

A. Final Product and Evaluation

The current progress represents the required analysis of the circuit before implementing the design into the RC airplane. The finding of the servo motor rotation in degrees from minimum to maximum is important for controls, which will be explored further in power-by-light testing. The dispersion between cable lengths will assist in the design of the complete fly-by-light airplane and assist in understanding minor errors that may be present with the servo motor.

To effectively analyze the EMI susceptibility of a design RPAS, the final product is broken down into multiple outputs stipulated by the deliverables. The desired final product of the RTF RC airplane will have a completed fly-by-light model. To follow on from the current progress evaluated, signal-by-light and power-by-wire will be implemented into the model; the analyzed optical fiber cables will substitute the servo motor's existing links, and a power-by-wire configuration will be designed to commence flight testing. The flight testing will comprise the following functionality tests [94] [95]:

- Basic operation test for powering up and powering down, additionally check for the center of gravity with respect to weight
- Monitoring the input and output signal to the servo motor whilst powered up, checking for temperatures, and doing control surfaces for directions (up, down, left, and right)
- Utilize a hard surface to test movement
- Conduct basic take-off into low flight and basic landing
- Progress flight tests in the air consisting of varied time periods and movement in the air

The system will be modified to eliminate power cables to the servo motor. Additionally, the power-by-light will be implemented into the model through optically controlled actuators. The flight test will be repeated for this system, monitoring the same functionalities required for EMI testing. The airplane will undergo EMI testing through low-band frequencies of 30 MHz to 200 MHz and potentially high-band frequencies of 200 MHz to 1 GHz. The testing equipment will include surge generators, power amplifiers, and spectrum analyzers. To further investigate the potential outcomes of EMI testing, contact with the AWE test facility will be pursued. These results found for the EMI susceptibility of the designed model will be compared to the same operation with a fly-by-wire model, specifically analyzing the survivability of each design. Once EMI testing has been organized, appropriate identification of testing characteristics that will address the aim of the project will be finalized. This will be done to further investigate the RPAS EMI susceptibility respective to their design, and how RPAS capabilities have been strengthened in the airspace as a direct result of implementing fly-by-light technology.

VIII. Conclusion

In this paper, a novel approach to implementing fly-by-light into an RPAS is proposed to contribute towards the EMI hardening of these systems. The project plan outlines the segments of work to undergo to achieve effective findings in deliverable tasks. The planning tool allowed for the potential difficulties to be foreseen, and the solutions to mitigate these difficulties or risks were discussed. The implementation of fly-by-light has been investigated in a variety of applications including test aircraft, rotorcraft, military aircraft through FOCSI, FACT, and FLASH programs, commercial airliners, and airships. The benefits deduced from extensive testing of fly-by-light applications have supported the ongoing research and capabilities of aircraft, including RPAS. Exceptional reduction of weight and increased speed form the baseline of benefits seen through implementing fly-by-light, leading to other critical improvements such as increased volume of transmitted information, effective temperature, and humidity survivability, and most noticeably, advantageous EMI immunity.

The current progress toward the final product has provided viable results toward receiving a PWM signal from an RC controller to a servo motor through an optical fiber cable. The pulse width difference between the minimum and maximum time provides 88° rotation of the servo motor for control measures. The dispersion of the signal through the 0.175 metre optical fiber cable resulted at 0.2165 ps/nm-km and was compared to the simulated findings of $8.65\text{x}10^{-4}$ ps/nm-km. The change of optical fiber cable length was a factor used to investigate dispersion effects, however, the practical findings concluded an increased time spreading of 0.7 ps between the 0.175 metre and 50 metre lengths, measuring dispersion at $7.5\text{x}10^{-4}$ ps/nm-km. The simulated components of dispersion guided the analysis of the practical results for monitoring realistic outcomes.

This project will continue to investigate and improve the implementation of fly-by-light into RPAS by delivering power to the system's components optically by replacing its existing electrical wires and testing the EMI susceptibility through rigorous procedures aligned with military standards. The potential extensions for the project will provide the ability to extend the research and continue collecting results for future research in this field, which includes visiting the AWE test facility in Edinburgh. The test results will enhance the current knowledge in this area of research and build a foundation for future capabilities for RPAS and other aircraft systems.

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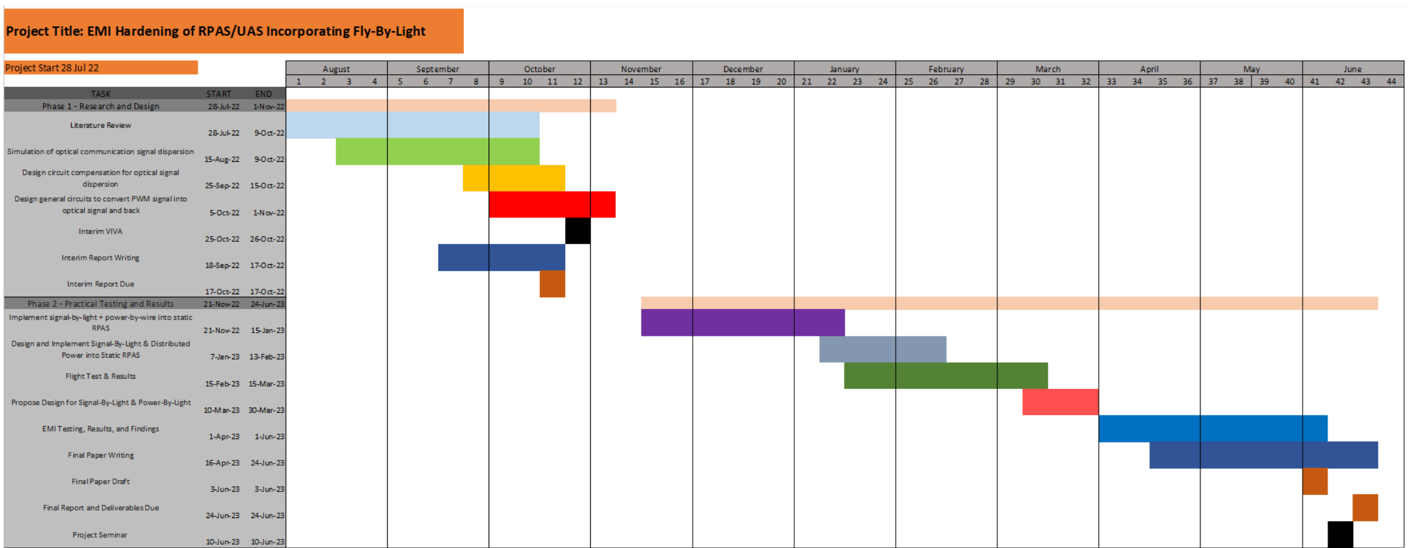
Appendix A
Maximum External EME for Fixed-Wing Aircraft Including UAVs

TABLE I: Table of Maximum External EME for Fixed-Wing Aircraft Including UAVs - Frequency Ranges and Electric Fields - Table 6 of MIL-STD464C

Frequency Range (MHz)		Electric Field (V/m – rms)	
		Peak	Average
0.01	2	88	27
2	30	64	64
30	150	67	13
150	225	67	36
225	400	58	3
400	700	2143	159
700	790	80	80
790	1000	289	105
1000	2000	3363	420
2000	2700	957	209
2700	3600	4220	455
3600	4000	148	11
4000	5400	3551	657
5400	5900	3551	657
5900	6000	148	4
6000	7900	344	14
7900	8000	148	4
8000	8400	187	70
8400	8500	187	70
8500	11000	6299	238
11000	14000	2211	94
14000	18000	1796	655
18000	50000	533	38

APPENDIX B
GANTT CHART - PROJECT PLANNER



Potential Difficulties:

1 Time constraints meeting deadlines - Overlapping tasks allows for insight to next task assisting in what is required, and prevents backtracking tasks, or introducing time issues that are not foreseen initially. Additionally, flight testing has been given sufficient time for possibility of unknown constraints.

2 Risk factors - Testing the UAV drone to EMI requirements in line with MIL-STD's. Compensated with organising alternatives, including EM Test Facility at RAAF Edinburgh.

3 Resource gaps - Acquiring UAV equipment and requirement to modify circuitry designs of PCB boards. PCB board availabilities are within three to four days of requesting, and can be constructed manually locally if required. Contacts for acquiring UAV equipment are available locally, allowing for immediate sources if required for further testing to account for possibility of damages, malfunctions, etc.

4 Consequences of interrelatedness - Each deliverable overlaps with each other for a period of time allowing for the identification of errors, or requirement for further work without adjusting overall time frames. This is most important for the writing of the final report, in conjunction with the EMI testing results, as well as the overlap of initial implementation of designs into a UAV and the flight testing. This ensures the outcomes are met, in an appropriate time, and conform to the remainder of the project timeframe.

Fig. 12: Gantt Chart with Task Timelines and Potential Difficulties Summarised with Implemented Strategies

APPENDIX C
SIMULATION OF 0.175 METRE CABLE DISPERSION EFFECTS

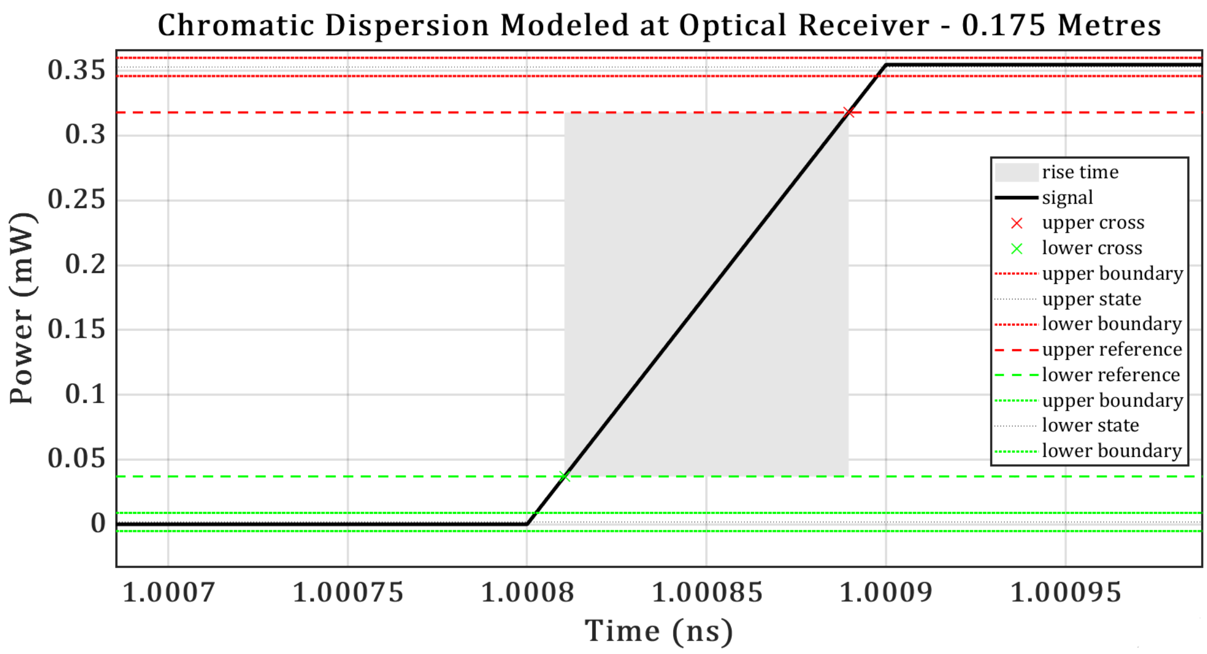


Fig. 13: Investigating the Pulse Width of the Simulated 0.175 Metre Cable for Dispersion Effects to Compare to Practical Results in PWM Conversion

APPENDIX D
TGY-IA6 2.4GHZ RECEIVER PWM INPUT SIGNAL

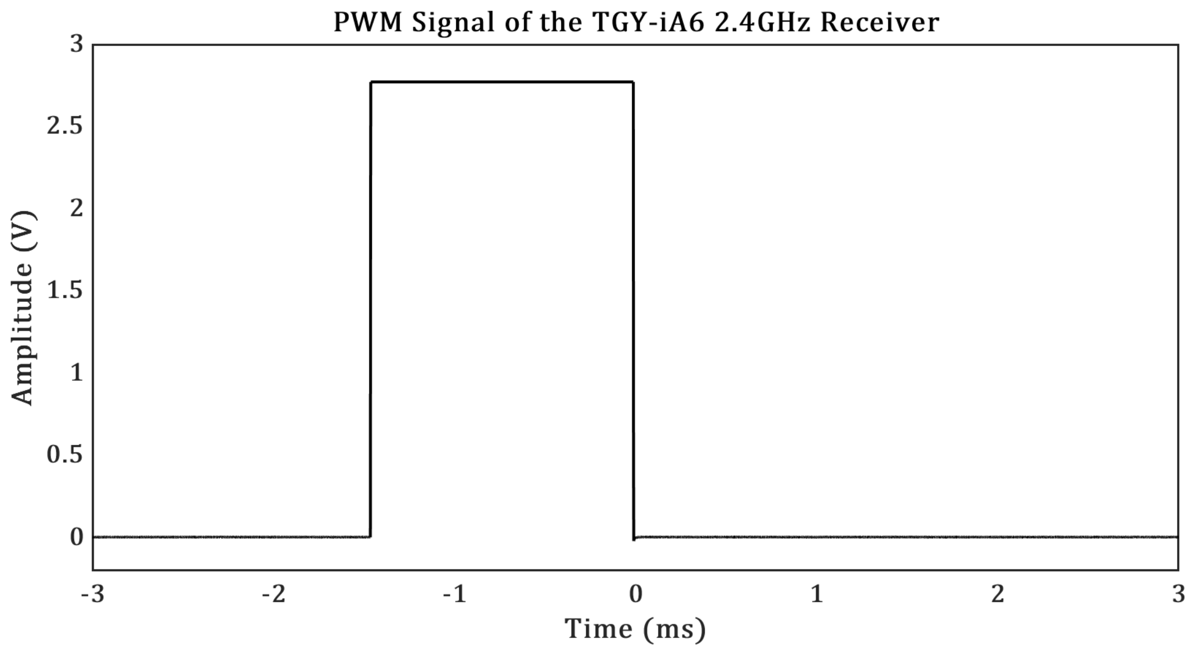


Fig. 14: PWM Signal of the TGY-iA6 2.4GHz Receiver - Input Signal to the Optical Transmitter Component - Pulse Width of 1.5 ms - Amplitude of 2.772 V with 5V Input

Appendix E
Interface Circuit Design for Conversion of PWM Signal through Optical Fiber Cable

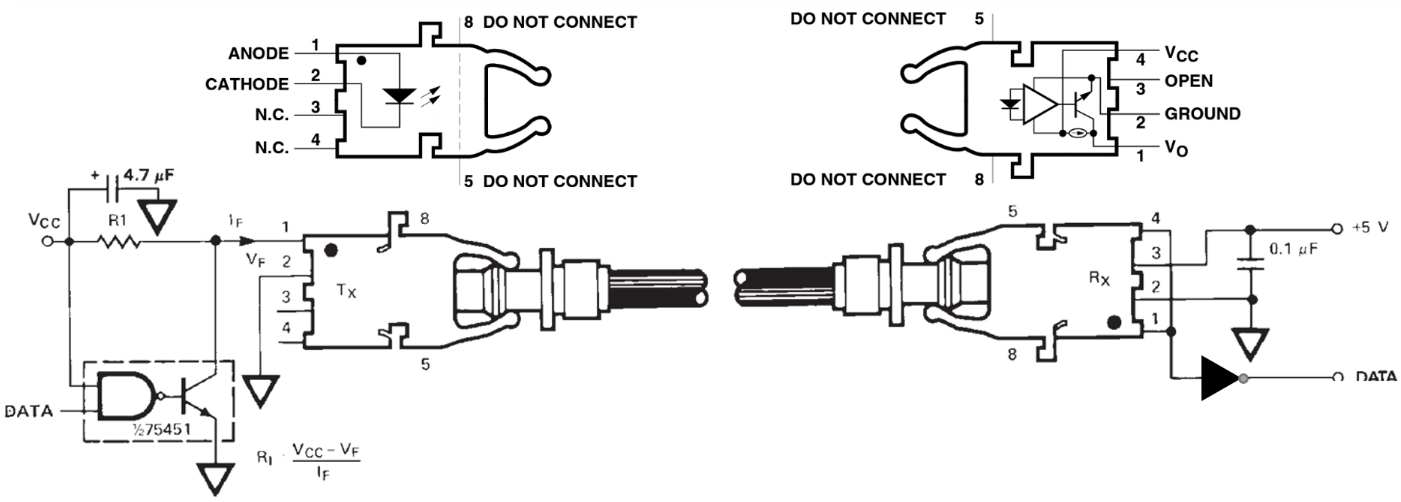


Fig. 15: Circuit Overview of Transmission Circuit with Low-Pass RC Filter - Circuit Overview of Receiver Circuit with Inverter Compensation - Transmitter and Receiver Pin out Diagrams Included

Appendix F
Inverted Output Signal to Servo Motor

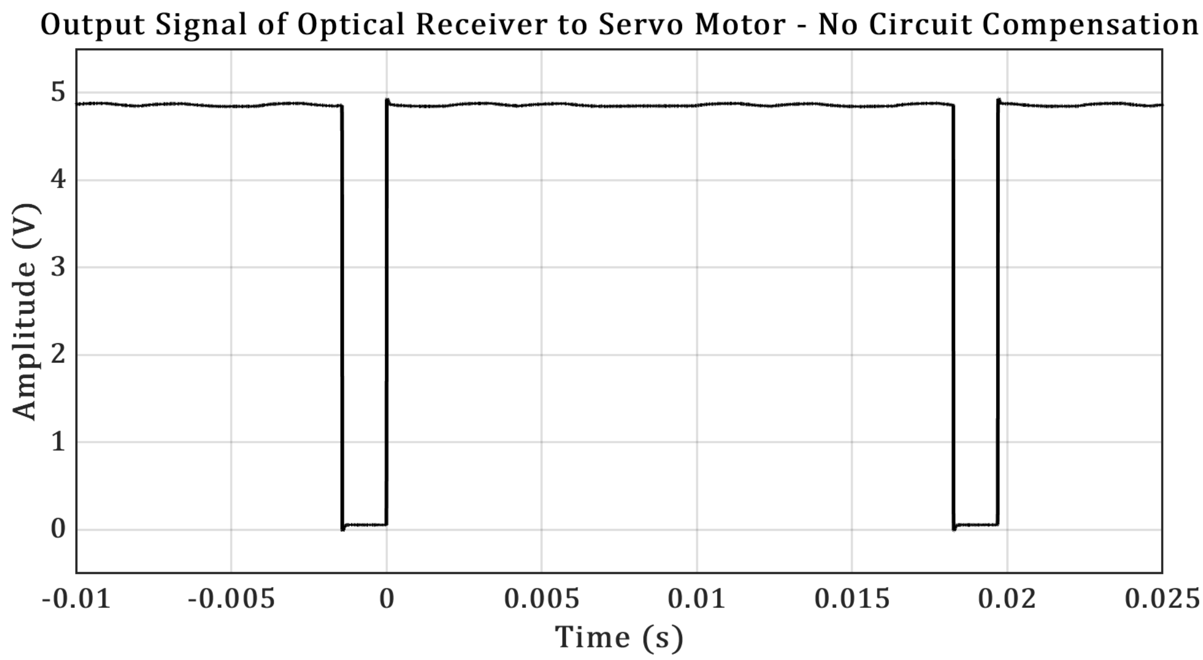


Fig. 16: Output Signal of Optical Receiver to Servo Motor with No Circuit Compensation - Inverted Signal

Appendix G
Input vs Output PWM Signal through 50 Metre Optical Cable

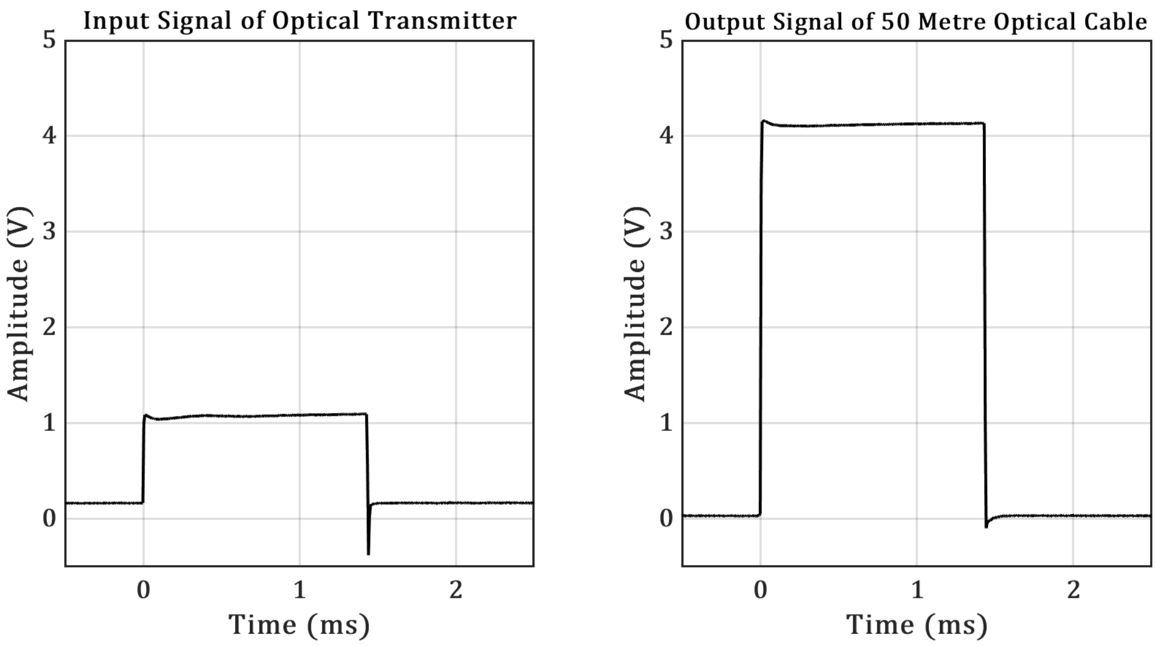


Fig. 17: Input Signal Compared to Output Signal through 50 Metre Optical Fiber Cable Investigating Dispersion

Appendix H
Various Output PWM Signal through 50 Metre Optical Cable - Compensated

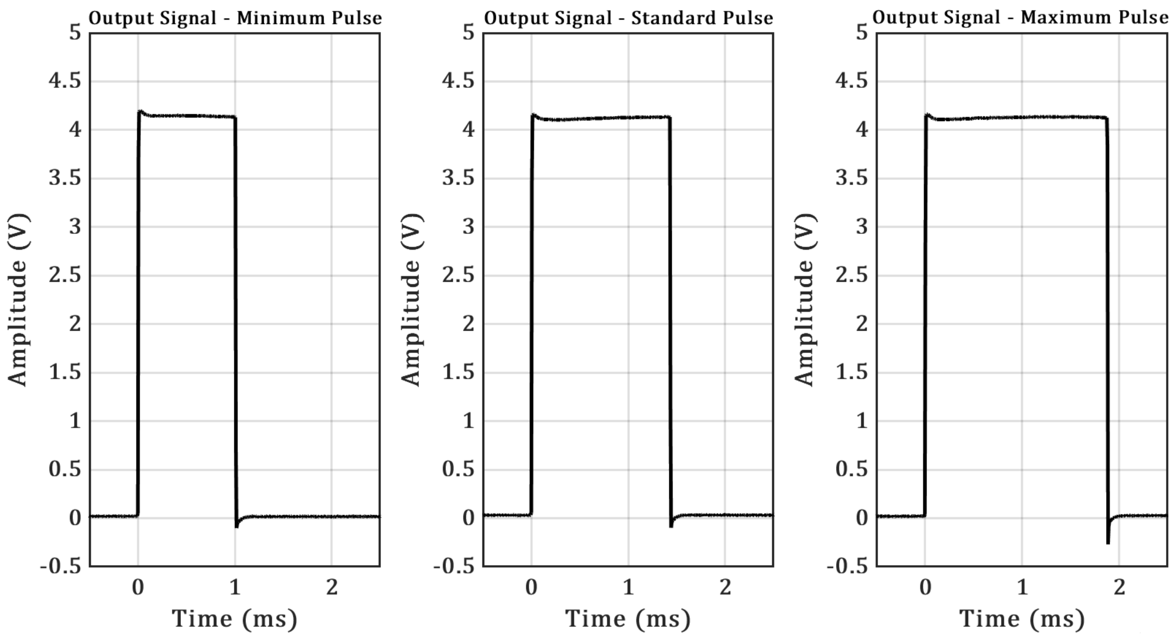


Fig. 18: Minimum, Standard, and Maximum Output Signal through 50 Metre Optical Fiber Cable Investigating Movement of Servo Motor