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Empirical Analysis of MAVLink Protocol Vulnerability for Attacking Unmanned Aerial Vehicles

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ABSTRACT Recently, unmanned aerial vehicles (UAVs), or the so-called drones, have been used in various applications. In particular, UAVs are used for rescue systems, disaster detection, and military purposes, as well as for leisure and commercial purposes. UAVs that are controlled over networks by ground control stations (GCS) can provide various services with expanded activity area. It is thus of critical importance to investigate the vulnerability of the drone system. In this paper, we focus on UAVs controlled by GCS over networks. We analyze the vulnerability of the micro-air-vehicle communication (MAVLink) protocol, which is one of the most widely adopted communication protocols for GCS-based control of UAVs. Then, by exploiting the vulnerability of the MAVLink protocol, we propose an attack methodology that can disable an ongoing mission of a UAV. Our empirical study confirms that the proposed attack can stop the attacked UAV and disable the mission.

INDEX TERMS UAV, UAS, drones, MAVLink, network attack, DoS, flooding attack, packet injection.

I. INTRODUCTION

Recently, unmanned vehicles (UAV)s, or so-called drones, have been widely used around the world. Drones provide various services. For example, a drone network can provide services for various drone applications [1], such as rescue systems [2], disaster monitoring [3], [4], commercial use, military missions, and so on.

An example of a commercial service using UAVs is Amazon's project Prime-Air, which was released in 2015 [5]. This system aims to design a future delivery service using UAVs. Various services utilizing UAVs such as Fleetlight [6] and Matternet [7] also have been released, as shown in Fig. 1. Services using UAVs are mainly performed in environments that are controlled over the networks as shown in Fig. 2. Controlling the UAV over a network allows the UAV to perform its mission without user control.

However, as the demands for services using UAVs is increasing, negative use cases are also rapidly increasing. For example, a drone with radioactive soil landed on the rooftop of the residence of the Prime Minister of Japan. In this light, methodologies that can disable malicious UAVs are needed.

In this paper, we focus on UAVs controlled by GCS over networks. We empirically analyze the vulnerability of the micro air vehicle communication (MAVLink) protocol, which is one of the most popular protocols used for GCS-based control of UAV [8]. It should be noted that few empirical studies on the vulnerability of the MAVLink protocol have been reported. By exploiting the vulnerability of the MAVLink protocol, we propose an attack methodology that can disable an ongoing UAV mission. We empirically validate the proposed attack methodology with a UAV testbed. Our experimental results confirm that the attacked UAV is stopped and the mission disabled.

Our contributions can be summarized as follows:

- We identify the vulnerability of the MAVLink protocol, a de facto standard for UAV and GCS communication.
- By exploiting the identified protocol vulnerability, we develop an attack methodology that can disable the UAV mission.

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FIGURE 1. Fleetlight and Matternet service.

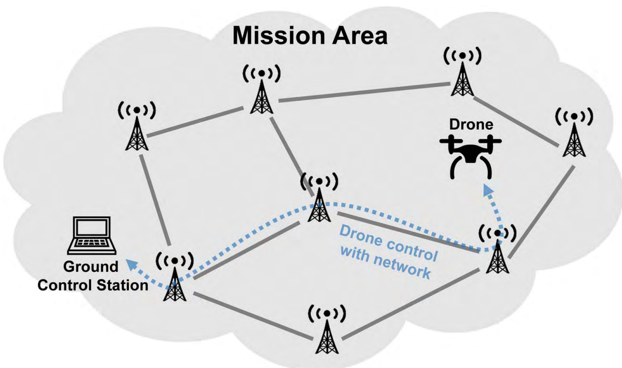


FIGURE 2. UAV system controlled over network.

The rest of the paper is organized as follows. In Section II, we provide background information on drone controls, the MAVLink protocol, and network attack methods. In Section III, we introduce the proposed method to disable a UAV. The experimental environment and the experiment scenarios are presented in Section IV. In Section V, we summarize existing work on disabling UAVs. Finally, Section VI concludes this paper.

II. BACKGROUNDS

Here, we provide background materials for our study.

A. DRONE CONTROL STRUCTURE

There are basically two ways to control a UAV, using a controller and using a ground control station (GCS), as shown in Fig. 3. In controller-based control, the user views the UAV directly or watches through a camera mounted on the UAV and controls it using the controller. The UAV and the controller are connected to a communication module, and the UAV is controlled by transmitting the controller's signal to the UAV in real time. Generally, the communication modules that are used are telemetry, Wi-Fi, ZigBee, and so on.

On the other hand, GCS-based control uses a computer to connect the managing software and the UAV; GCS then performs mission commands uploaded by the user. GCS can monitor the status of the UAV by receiving information of various sensors mounted on the UAV such as current altitude, speed, map position, and current mission status. The controller-based method can manually control the UAV in real time whereas GCS-based control enables stable flight as well as unassisted flight to complete autonomous missions. Here, we consider GCS-based control for the present study.

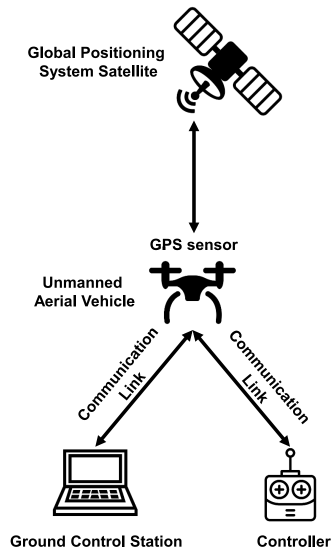


FIGURE 3. Two methods of drone control: GCS vs. direct controller.

B. MAVLINK PROTOCOL

Here, we focus on the MAVLink protocol, which is one of the most widely used protocols for GCS-based drone control. The MAVLink protocol is a message-based UAV communication protocol developed by Lorenz Meier in 2009 [8]. This protocol is a part of the current DroneCode project and is used by thousands of developers. It is also used in numerous Autopilot-based systems such as ArdupilotMega, pxIMU Autopilot, and SLUGS Autopilot [9]. MAVLink packets are bidirectionally transferred between a UAV and a GCS as header-based messages. The GCS sends mission commands to the UAV, and the UAV transmits state information including the sensor value and current position to

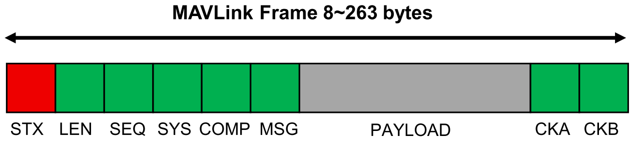


FIGURE 4. MAVLink protocol data frame structure [8].

the GCS. Fig. 4 shows the message structure of the MAVLink protocol and Table 1 shows the meaning of the MAVLink frame [8].

TABLE 1. Meaning of the MAVLink frame [8].

Byte Index	Content	Value	Explanation
0	Packet Start Sign (STX)	0xFE	Indicates start of a new packet
1	Payload Length (LEN)	0-255	Indicates length of the following payload
2	Packet sequence (SEQ)	0-255	Packet transfer sequence information for detecting packet loss
3	System ID (SYS)	1-255	ID of the sending system; Allows to identify multiple platforms on the same network
4	Component ID (COMP)	0-255	ID of the sending component; Allows to identify multiple components on the same platform
5	Message ID (MSG)	0-255	ID of the message; Define what payload means, and how to decode it
6 to (n+6)	Data (Payload)	0-255 (bytes)	Data of message; depends on the message ID
(n+7) to (n+8)	Checksum (CKA and CKB)	ITU X.25/SAE AS-4 hash of bytes 1 to (n+6); It includes MAVLINK_CRC_EXTRA parameter computed from message fields	

C. NETWORK ATTACK

Network attacks violate the confidentiality, integrity, and availability of the system. Confidentiality only allows authorized users to access information on the system. If confidentiality is violated, it is possible to eavesdrop on information and spoof the system. Integrity means the original information and signals transmitted, stored, and converted are maintained and not changed afterward. Violation of integrity allows attacks such as message injection, replay attack, and so on. Availability allows the system to function for the time required by the user. In terms of maintenance, service must not be interrupted and performance must be maintained. Also, in terms of access to the system, the service must be accessible whenever the user needs it. Denial of service attacks can violate availability.

1) MAN-IN-THE-MIDDLE

Man-in-the-middle (MITM) is an attack that violates the confidentiality or integrity of the system [10], [11]. As indicated by the name, the attacker is located in the middle of the hosts and sniffs information [12]. The attacker can cause hosts to communicate information to the attacker. This is possible because the system allows the host to set the destination address to the attacker's address for address resolution protocol (ARP) poisoning. When MITM is applied to a UAV system, it is possible to eavesdrop on all of the information transmitted between the UAV and GCS.

2) EAVESDROPPING

Eavesdropping is an attack that violates the confidentiality of the system; it means that an attacker steals and listens to information of other users. If a MITM attack succeeds, eavesdropping can be enabled [12]. One of the methods to protect the system from eavesdropping, it is necessary to encrypt the message.

3) DENIAL-OF-SERVICE

Denial-of-Service (DoS) attacks violate availability, monopolizing the resources of the system; using both DoS and MITM, it is possible to prevent other users from using system services [13]. In a DoS attack on a UAV system, control message, sensor information, and mission information are not correctly transmitted. Therefore, the UAV is not maintained in the stable state and furthermore the mission execution cannot be performed correctly.

4) POTENTIAL THREATS TO UAV SYSTEMS

In a UAV system, it is possible to have different vulnerabilities for each component of the system. Therefore, the potential threats that may occur for each component may differ. The threats that can occur for each component of the UAV system are classified by the security objective [14]–[17]. Table 2 shows the potential threats that may occur for each component of the UAV system.

TABLE 2. Potential threats on UAV systems.

Security objective	System objective	Attack method
Confidentiality	GCS	Virus
		Malware
		Keyloggers
		Trojans
	UAV	Hijacking
	Communication Link	Eavesdropping
		Man-in-the-middle
Integrity	Communication Link	Packet injection
		Replay attack
		Man-in-the-middle
		Message deletion
Availability	GCS	Denial of service
	UAV	Fuzzing
	Communication Link	Jamming
		Flooding
		Buffer overflow

III. PROPOSED ATTACK METHODOLOGY

A. VULNERABILITY OF THE MAVLINK PROTOCOL

Since the MAVLink message is a header-based protocol, it checks the first frame of the data packet and classifies the message. Therefore, it checks the STX value which is the

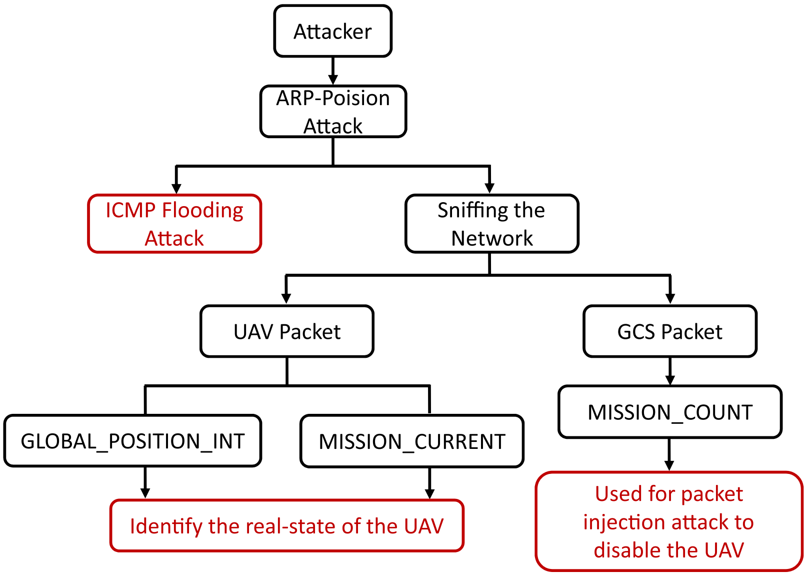


FIGURE 5. **Overall procedure of UAV attack scenarios.**

initial frame and recognizes whether it is a MAVLink packet. To improve transfer speed and efficiency, the MAVLink message does not perform encryption [8]. When a message is encrypted, because the value of the header of the packet changes, the system does not recognize it as a MAVLink packet. Furthermore, it takes additional time to decrypt the data. Hence, the MAVLink protocol does not introduce encryption. Therefore, the MAVLink protocol has a security vulnerability due to non-encrypted messages.

B. PROPOSED ATTACK SCENARIO

Here, by exploiting the vulnerability of the MAVLink protocol, we propose a methodology to disable a UAV. In particular, we exploit the fact that the MAVLink message is not encrypted. Accordingly, after sniffing the UAV network packets, we inject packets to disable the UAV. We consider a UAV system in which the UAV and GCS are connected via a network and the attacker has already hacked into the network, which is possible by various existing methods.

The attack scenario is as follows: In order to decide on an attack target, it is necessary to have information on the hosts connected to the network. Therefore, an attacker operates in the promiscuous mode and obtains all the packets and sets the target. The attacker obtains the GCS and UAV packets by using an ARP poisoning attack, which sends fake ARP information to the host and causes the packet to be forwarded to the attacker.

By executing packet sniffing on the drone network, an attack can obtain the MAVLink packets. There are 160 kinds of common MAVLink packets; these packets send UAV state information or GCS commands in the MAVLink payload. By analyzing the packets to be transmitted, it is possible to identify whether the UAV is currently in flight, the state of the battery, and what mission is being executed.

Based on the information, the attacker can identify the actual state of the UAV and can disable the UAV by sending malicious packets to it. In this study, we use an ICMP flooding attack as well as a packet injection attack which exploits the vulnerability of the MAVLink waypoint protocol. Fig. 5 summarizes the overall procedure of the attack scenarios.

C. VULNERABILITY OF MAVLINK PROTOCOL TO FLOODING ATTACK

Internet control message protocol (ICMP) checks the connection status of the hosts in the network and reports when there is a problem with packet transfer. Using the ping command with a Windows command or Linux kernel, an ICMP message can be sent. When sending an ICMP message, the sender will send an ICMP request packet to the receiver. The receiver that has successfully received the request message will then respond to the sender. If the sender sends a large number of request messages, the receiver will be too overloaded to check and send replies. In this way, the ICMP flooding attack overloads the target system and invalidates the service. In section IV, by conducting an ICMP flooding attack, we verify its effect on a UAV.

D. VULNERABILITY OF MAVLINK WAYPOINT PROTOCOL TO PACKET INJECTION ATTACK

When using a GCS to control the UAV, the UAV executes the mission commands sent by the GCS. At this time, mission commands are executed based on the waypoint protocol [30] in the MAVLink protocol. Fig. 6 shows the MAVLink waypoint protocol procedure. When the user completes the mission commands setting, the GCS sends information on the total number of missions as a MISSION_COUNT (N) message. Upon receiving this message, the UAV requests the first mission information using the MISSION_REQUEST (0)

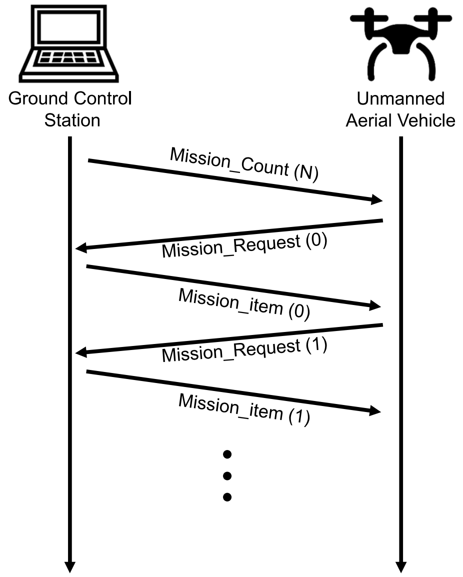


FIGURE 6. **MAVLink waypoint protocol procedure.**

message. In response to this message, the GCS sends the first mission information with a MISSION_ITEM (0) message. In this way, the GCS sends a total of N pieces of mission information to the UAV. Upon completion of the mission information transfer, the UAV transmits a MISSION_ACK message to the GCS to notify that the transmission is completed.

We exploit the vulnerability of the waypoint protocol and carry out experiments with a packet injection attack. When the GCS sends a MISSION_COUNT (N) packet, the UAV erases the stored mission information and prepares to receive new mission commands. Using these features, we conduct the experiment according to the following scenario. Because the attacker has intruded the network, the attacker is able to eavesdrop the information between the GCS-and the UAV and obtain the mission information. After this, when the UAV executes the mission and starts the flight, the attacker sends an eavesdropped MISSION_COUNT (N) packet to the UAV and initializes the mission information. The UAV sends a MISSION_REQUEST to the GCS to request mission information, but the GCS has already sent mission information and hence will not transmit. Therefore, the UAV enters a standby state waiting for mission information. In section IV, we empirically verify that the UAV under packet injection attack is disabled.

E. PACKET MONITORING AND INJECTION

In order to decide on an attack target, it is necessary to have information about the hosts connected to the network. Using Cain & Abel [24] as a network sniffing tool operating on Windows OS, we can obtain information on the hosts connected to the network. We used Cain & Abel to learn the network IP address of the UAV and the GCS. Also, we obtain the GCS and UAV packets by using an ARP poisoning attack, which sends fake ARP information to the host and causes

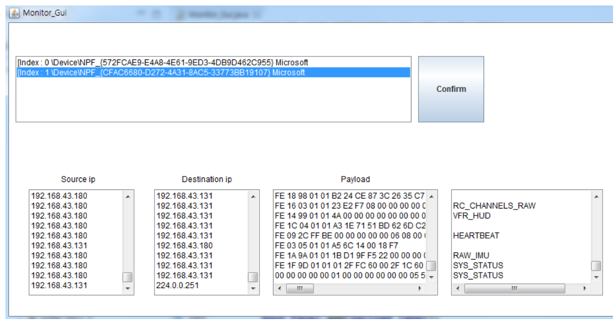


FIGURE 7. **Monitoring program developed using Jpcap library.**

the packet to be forwarded to the attacker. Therefore, in UAV networks, packets of UAV and GCS can be transmitted to an attacker.

Jpcap [25] is a Java-based library that captures network packets. Using Jpcap to monitor the state of the UAV, in this study we develop a packet capture tool. Fig. 7 shows the developed program. As shown in Fig. 7, the program shows the network interface, source IP address, destination IP address and payload. The payload indicates the type of MAVLink data, which makes it possible to check the Message_ID of the MAVLink data. Using this program, we can estimate the state of the UAV in real time. For example, it is possible to confirm the MISSION_SET_CURRENT packet and determine what mission is currently being executed and whether or not the UAV is in flight. Therefore, we can know when to attack the UAV by monitoring its state information.

We use Packet Sender [26] to inject attack packets into the UAV. This program can send UDP and TCP network packets. Using this program, it is possible to transfer packets by changing to the payload desired by the user.

IV. ATTACK IMPLEMENTATION

A. TESTBED CONFIGURATION

In order to perform experiments in the UAV network, we construct a testbed as shown in Fig. 8. We install hostapd [27] in raspberry-pi3 for the wireless access point, which will be

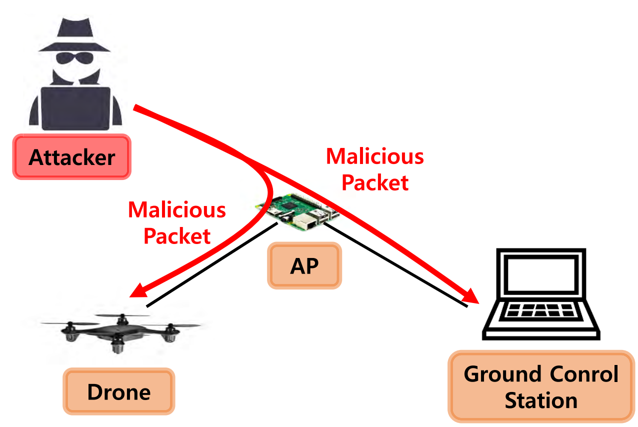


FIGURE 8. **Testbed configuration with AP, GCS, and drone.**

FIGURE 9. 3DR X8+ drone used for experiments.

FIGURE 10. Mission planner used for experiments.

used for connecting the UAV and GCS. We use 3DR X8 + drone in Fig. 9 for our experiments. Since this drone uses pixhawk, it can be controlled using the MAVLink protocol. In order to allow the drone to connect to the access point, we use raspberry-pi3, which includes installing mavproxy [28]. The GCS used for the experiment is the mission planner [29] as shown in Fig. 10.

B. ICMP FLOODING ATTACK

In an environment connected to an access point, we carry out experiments with the effect of an ICMP flooding attack on a UAV. First, Fig. 11(a) shows the change in the inter-reception time of sensor values when sending ICMP packets to the UAV when the attacker sends ICMP request packets to the GCS and the UAV at 7 Mb/s. In this experiment, we select pitch values for the UAV. The normal case is shown in Fig. 11(a); it can be easily confirmed that the inter-reception time does not greatly deviate from the average of 0.24, but that this value changes significantly in the case of the ICMP attack. In the normal case, the variance of the inter-reception time is measured to be about 0.238×10^{-3}; in the case of the ICMP attack, the variance of the inter-reception time is measured to be about 8.4×10^{-3}. The variance of the inter-reception time during the ICMP attack is about 35 times larger than that of the normal case.

Fig. 11(b) shows the change in the inter-reception time of pitch values when sending ICMP packets to the GCS. In this figure, the variance of the inter-reception time in the normal case is measured to be about 0.238×10^{-3}; in the case of the ICMP attack, the variance of the inter-reception time is measured to be about 2.42×10^{-3}. The variance of the inter-reception time for the ICMP attack is about 10 times larger than that of the normal case. In this experiment, we confirm that the variance of the packet inter-reception time is larger for an ICMP flooding attack on the UAV.

We also conduct an experimental ICMP flooding attack on a UAV that is executing a mission. In this experiment, we confirm that the UAV's sensor values are not transmitted well, and the mission commands delivered by the GCS are also not transferred properly. A heartbeat message is sent between the GCS and the UAV in a one second period to maintain the connection. If the heartbeat message is not received during

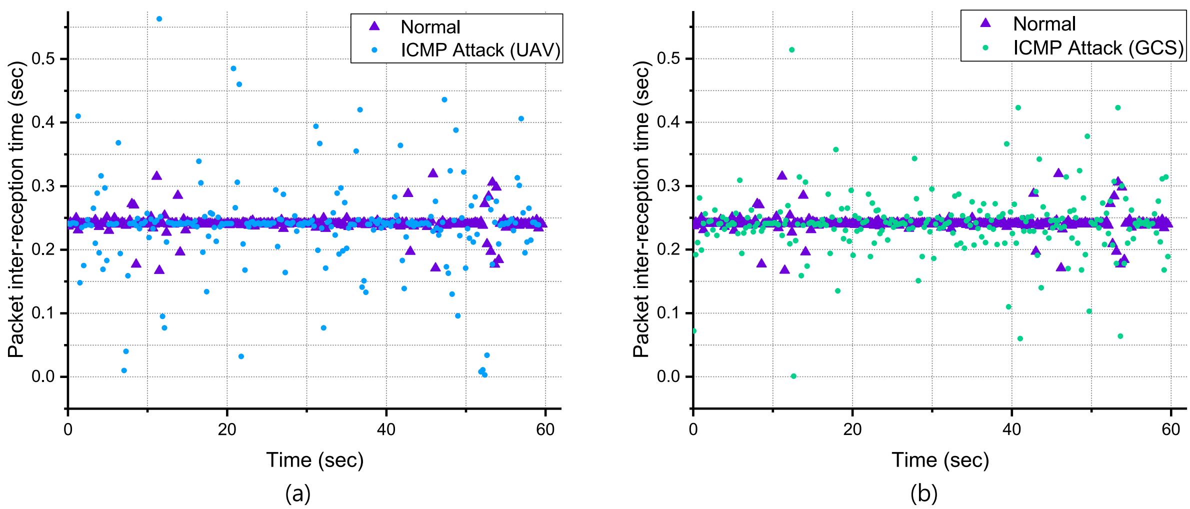
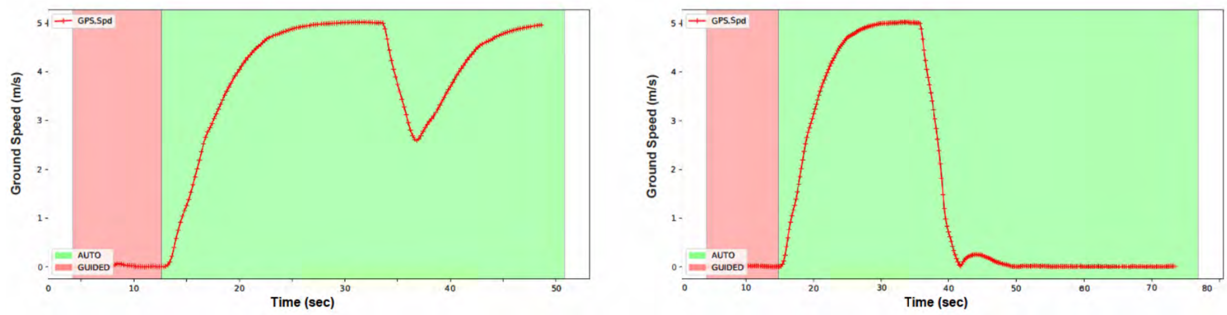


FIGURE 11. Packet inter-reception time under normal operation and under ICMP attack on UAV and GCS.



(a) (b)

FIGURE 12. **Ground speed under normal operation and under packet injection attack.**

a period longer than three seconds, the UAV will operate in failsafe mode. In this experiment, because of the ICMP flooding attack, the UAV cannot receive a heartbeat message within three seconds.

C. PACKET INJECTION ATTACK

We carry out experiments to transmit MISSION_COUNT (N) packets to the UAV executing its mission. From the experiment, we confirm that the UAV starts to hover immediately after receiving the MISSION_COUNT (N) packet. This is because all of the mission information that the GCS has sent before is deleted due to the forwarded MISSION_COUNT (N) packet.

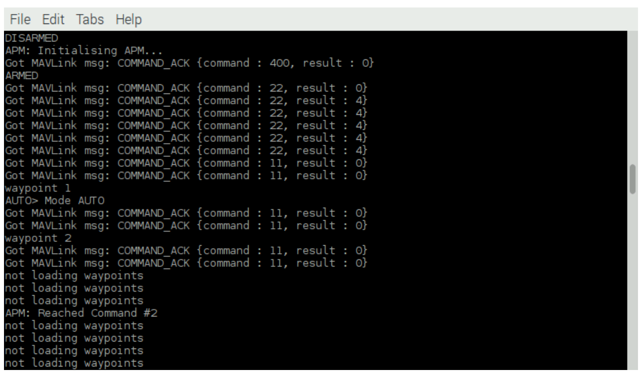


FIGURE 13. **Mavproxy command screen.**

Fig. 13 shows the console screen of the UAV mavproxy that receives the packet of MISSION_COUNT (N). In Fig. 13, "not loading waypoint" appears on the console screen after receiving the MISSION_COUNT (N) packet while waypoint 2 is executing. In this state, the UAV continuously hovers unless the battery is exhausted or a new mission command is transmitted. When the UAV is in the hovering state, if an attacker injects a packet containing mission information, the UAV will execute the mission sent by the attacker. Our experiment can be found in [32]. Other UAV attacks usually cause unpredictable secondary damage due to the UAV crashing to the ground, whereas our attack does not cause crashes because the UAV is forced to hover. Fig. 12 shows how the ground speed varies with and without the attack. The ground speed is the relative speed of the UAVs with respect to the ground. Thus, the ground speed is an effective indicator to show the behavior of the UAVs, i.e., whether it is hovering or carrying out its mission. Fig. 12(a) shows the ground speed of the UAV without any attack. When the time instant is around 35 seconds in Fig. 12(a), the ground speed decreases due to waypoint change of the UAV mission. Fig. 12(b) shows the ground speed of the UAV under a packet injection attack. We perform the packet injection attack just before the waypoint of the UAV is changed. In Fig. 12(b), we can see that the UAV stops the mission under the packet injection attack and hovers for a few seconds.

D. SOFTWARE IN THE LOOP (SITL) SIMULATOR

Here, with the software in the loop (SITL) simulator [31], the experiment scenario conducted in Section IV.B and C is performed in the same way. We used the mission planner as the GCS and connected the UAV to mavproxy in SITL.

First, we conduct experiments with SITL on how ICMP flooding affects the UAV. As in the previous experiment, it is confirmed that the packet inter-reception time greatly fluctuates.

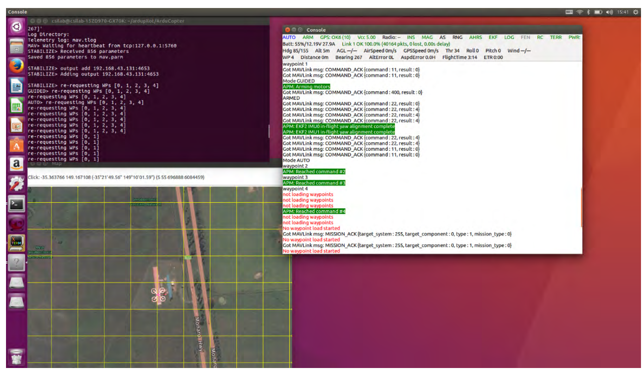


FIGURE 14. **Experiment using SITL simulator.**

In addition, the same scenario as used for the packet injection experiment conducted previously is used with SITL. Fig. 14 shows the packet injection experiment in SITL.

Fig. 15 shows the UAV mavproxy console screen after execution of SITL. As in the previous experiment, when the UAV receives the MISSION_COUNT (N) packet, we can confirm that "not loading waypoints" is displayed on the command screen. Similarly, our experiment with SITL can be found in [33].

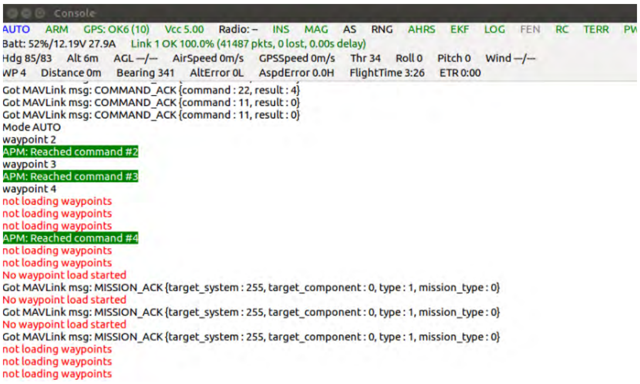


FIGURE 15. UAV mavproxy console screen executed in SITL simulator.

V. RELATED WORK

One way to disable a UAV is to use a sensor and hardware attack on the UAV, or a network attack. Sensor and hardware attacks make use of UAV sensor vulnerabilities to disable the UAV. In general, communication link jamming and GPS spoofing are used for sensor attacks in UAV systems. Jamming prevents the communication link between the UAV and the GCS or the controller from correct operation so that the control message of the UAV cannot be transmitted. In the structure of the UAV system shown in Fig. 3, GPS spoofing is a scheme utilizing the vulnerability of the communication between the GPS satellite and the UAV GPS sensor. A GPS spoofing attack is used to trick the UAV by broadcasting a fake GPS signal [9], [15]. In the case of a real GPS signal, the distance between the satellite and the sensor is long, and therefore the GPS signal power can be weakened. Thus, it is possible to transmit fake GPS information to the UAV by generating GPS signals near the UAV. Tippenhauer *et al.* [18] study a GPS spoofing attack on the GPS receiver. These attacks either require special equipment or have a limited attack range, whereas our attack method can be carried out without any special equipment and distance constraints.

Rani *et al.* [10] conduct research to disable a UAV by attacking the access point in Wi-Fi networks. In this research, the authors use the vulnerability of wired equivalent privacy (WEP), which is one of the WiFi security protocols. WEP encryption has a vulnerability that makes it possible to crack the pre-shared key by collecting a certain amount of data. In particular, using the password crack tool aircrack-ng, it is easy to crack the pre-shared key value in WEP encryption. Using aircrack-ng, the authors disable the UAV by sending de-authentication packets to the UAV. This attack is only applied to UAVs that use Wi-Fi as a communication protocol, whereas our attack method can be applied to any UAV systems using the MAVLink protocol.

Rodday *et al.* [19] carry out an experiment to disable a UAV using a man-in-the-middle attack. In this system, the authors use the Zigbee API mode, which can send broadcast packets to UAV networks. The broadcast packets collect the initial vector values, which are used to crack the WEP. As in [10], Rani *et al.* used the vulnerability of WEP to hack the UAV. This attack method can only attack a specific manufacturer's UAV. On the other hand, since the MAVLink protocol is a de facto standard, our attack can be considered a more general approach.

In [20], a method to hijack a UAV using the vulnerability of the MAVLink protocol is proposed. When using the telemetry module to control the UAV via MAVLink, it is necessary to enter the NetID to connect to the UAV. Therefore, if the NetID is known, it is easy to hijack the UAV. Exploiting this, Highnam *et al.* [21] execute an attack by using an antenna with the same NetID to repeatedly send malicious MAVLink packets. Unlike this approach, our attack method does not require any additional information such as NetID.

Samland *et al.* [22] and Pleban *et al.* [23] hijack a UAV using the vulnerability of the AR drone. In particular, Samland *et al.* [22] use port scanning of the FTP port and then sent a malicious code to the UAV to access the UAV's private pictures and information without permission. Also, Pleban *et al.* [23] perform an attack using an AR drone's telnet port vulnerability to re-install the shell script and restart the AR drone. In this way, they easily stole the authority of the AR drone.

VI. CONCLUSIONS

In this paper, we have empirically studied the vulnerability of the MAVLink protocol. By exploiting the unencrypted messages of the MAVLink protocol, we have devised an attack methodology to disable a UAV. In our experiments, first, we have studied an ICMP flooding scenario, and we confirmed that the packet inter-reception time significantly fluctuates which can be fatal to the UAV. We have further carried out packet injection experiments, where we have exploited the vulnerability of the waypoint protocol to send malicious packets for deleting mission information of the UAV. Consequently, under the packet injection attack, the UAV on the mission has stopped and hovered because of deleted mission information. In summary, we have identified the vulnerability of the MAVLink protocol and have verified it with an empirical study.

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