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Simple Design and Implementation of Two-Way Communication System through UAV

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h*Abstract*—**In this paper, an Unmanned Air Vehicle (UAV) which can carry and communicate with an Unmanned Ground Vehicle (UGV - Rover) is designed and realized. In this context, one UAV and one Rover are designed separately. The Rover is designed much smaller than the UAV as it is carried by the UAV and it can make its own movement after leaving the UAV near the area where it will be operated. At this stage, the carrier UAV acts as a communication relay, providing communication between the central control station and the Rover. Using nRF24L01 transceiver modules on each of the central control station, carrier UAV and the Rover, communication between them is achieved via programming as being master or slave. The relay communication system is designed on Serial Peripheral Interface (SPI) protocol of nRF24L01 transceiver modules. The Rover is also equipped with a camera on it to record videos and to take pictures. Both the UAV and the Rover were designed especially in order to reduce the energy consumption of them. Hence the Rover is designed as small in size and light as possible. By taking into account the equipment, batteries and motors that the vehicles will carry, the best design has been tried to be implemented in order to increase their ranges and reduce energy consumptions. It is possible to use it in the defence industry for military purposes, in places where bomb detection or long-range access is difficult with a single UAV, where land access is required.**

Index Terms—**Relay Communication, nRF24L01 Module, UAV, UGV, SPI.**

I. Introduction

WITH THEIR high mobility and low cost, Unmanned Aerial Vehicles (UAVs), also commonly known as drones or remote-controlled aircraft, have found wide application in the last few decades [1]. Historically, drones were primarily used in the military, mostly deployed in enemy territory to reduce pilot casualties. With continued cost reduction and device miniaturization, small drones (typically not exceeding 25 kg) are now more easily accessible to the public. Therefore, numerous new applications have emerged in civil and commercial areas with typical examples including weather monitoring, wildfire detection, traffic control, cargo transportation, emergency search and rescue, communications relaying etc. [2], [3]. Many different vehicles (another drone or Unmanned Ground Vehicles (UGV)) can work simultaneously with these developing drones. They can act together in different missions as military or civilian and can perform tasks in cooperation. Monitoring and inspection tasks can be done with the drone, but in more sensitive missions the drone will not provide maximum benefit [4], [5]. More sensitive tasks can be performed with more sensitive vehicles like UGVs that can work with drones [6], [7], [8]. The communication with UGVs can be done both bilaterally and via drone. It means, the UGV can be guided autonomously by both human and drone [9], [10]. In some instances, multiple tools can work together to perform a task. No matter how much companies use this technology for military purposes, interaction between ground vehicles and drones will be seen more frequently in the following years and many different examples will be seen in the coming years.

The paper is organized as follows. In section 2 problem is defined clearly. Section 3 explains the design steps of both UAV and the Rover. Two-way communication between the units are given in section 4 and section 5 concludes the paper.

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II. Problem Definition

The main purpose of this paper is to design an UGV (Rover) and an UAV that carries the Rover. Also their communications with each other and with the central control station problem is solved. This design can be used for the following purposes;

1) to be able to use it for applications that cannot be realized from the air and must be carried out from the ground.
2) to be able to collect data in a confidential way with the advantage of its small size in narrow and difficult regions to enter.
3) being able to deploy the Rover in longer distances with the help of communication established in areas where the UAV's range will not be enough.

The carrier UAV will pick up the Rover from its current position to move it to the desired location. When the carrier UAV arrives at its planned location, it lands and then releases the Rover. The carrier UAV begins to act as a communication relay so that it can communicate with the Rover and the central control station. After communication link is established, commands from the central control station pass over the carrier UAV and are transmitted to the Rover. The Rover performs the required missions and is taken back by the carrier UAV and is returned back to the safe zone. This case is illustrated in Figure 1 and Figure 2.

Fig. 1. Realization of Project.

While the Rover performs the planned mission, the UAV operates in standby mode, consumes less energy and provides the communication between Rover and central control station. The UAV should be especially capable of carrying the Rover and be supported with equipment that can communicate with central control station during its flight. Moreover, Rover and the UAV must be designed to provide maximum flight time and consume less energy as possible. Details of the designs are more clearly explained in the design sections. The most important problems are to implement the two-way communication between the central control station-UAV-Rover and to design optimum UAV and Rover in terms of energy consumption and operation range.

Some mathematical calculations for weight lifting of the UAV and for motor and other device selections are included in the next sections.

III. Design of UAV

The 3 dimensional (3D) frame of the UAV was designed in SolidCad completely within the aerodynamic requirements. The UAV main body was determined to be an octocopter to fit for our purposes as shown in Figure 3 [11].

The main material of the UAV was determined as aluminium due to strong and easy-shaped characteristics. Aluminium

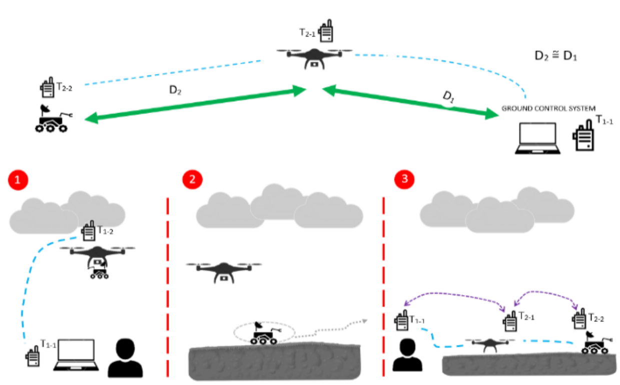

Fig. 2. Communication Schematic of Project.

Fig. 3. UAV‘s 3D Frame Drawing In Computer.

materials were cut to the specified dimensions and the octocopter frame was welded to each other. The use of aluminium material normally provides a disadvantage in weight compared to carbon fibre material. However, this situation has been turned into a completely advantageous situation with the original design. The aluminium octocopter UAV, which we have created with our own unique design, provides 700 grams of lightness compared to normal carbon fibre frames. The combination of aluminium parts is provided by welding. Welding the arms of the frame that are separated to each other with the straight aluminium pipe in the middle, has also eliminated the strength problem. In this way, the UAV was created entirely with novel and original design. At the same time, the lightness provided has given us a positive advantage in lifting weights.

A. Thrust and Performance Calculations

The following calculations were made for motor and thrust calculations, respectively. As a result, compatible parts were determined for the purpose of the project. The total flight weight of the UAV (together with own weight and load) depends on the performances of the engines as below, program.

$$W_t = 2.19 \times T_{tp} \tag{1}$$

where W_t is the total weight (flight weight) of the UAV and T_{tp} is the total performance of the engines. After design is finished and the total weight of the UAV and the load is determined, by using Eq. 1 total engine performance required for this design can be determined and then each engine can be chosen easily. On the other hand, to calculate total weight of the drone, we need to determine engine due to the requirement of their weights. Then we need to check the selected engines satisfy the requirement given in eq.(1). The list of the selected parts of the UAV and their weights can be seen in Table I.

As it can be seen from Table 1, the total weight of the main components of the UAV was calculated as 3868 grams. This value is the total weight of the UAV when carrying the maximum load. By using the Eg.1 and the flight weight calculated in Tab. I, the thrust value of the motor can be calculate as [12];

TABLE I
WEIGHT OF UAV BODY EQUIPMENT.

Tool	Weight(gram)
Aluminum frame	680
Undercarriage body	224
Sunnysky X4108S brushless motor (8 pcs)	110 X 8 = 880
1245 propellers (8 pcs)	10 X 8 = 80
Battery (24 pcs)	48,5 X 24 = 116
Load (Rover)	840
Total	**3868 g**

$$3868 \times 2,19 = 8470,92\ g \tag{2}$$

According to the result above, 8470,92 g is the total thrust required by the motors. Due to octocopter case, 8 motors are used in the UAV design. Thrust force for each motor can be calculated as,

$$8470,92 \div 8 = 1058,87\ g \tag{3}$$

Each motor must apply 1058.87 grams of thrust. When the motors are compared in these standards, the selected engine (Sunnysky X4108S brushless motor) is found suitable for use in our design. The technical parameters of the selected motor is listed as in Tab. II.

TABLE II
TECHNICAL TABLE OF MOTOR [13].

Propelller (inch)	Voltage (V)	Current (A)	Thrust (g)	Power (W)	Efficiency (g/W)
		1	250	22.2	11
		2	430	44.4	9
		3	590	66.6	8
		4	720	88.8	8
		5	840	111	7
APC 1238	22.2	6	960	133.2	7
		7	1060	155.4	6
		8	1160	177.6	6
		9	1250	199.8	5
		10	1330	222	5
		11.7	1520	259.74	5

By looking at the Tab. II, we can see this motor can generate thrust from 250g up to 1520g. Our required maximum Thrust value for each motor is 1058,87g, therefore this motor can supply more power than required. It means these motors can be used safely to carry Rover. Our battery unit will supply 12A of current to the engines, on the other hand the nearest upper value of 1058,87 g is 1060g in table 2. Hence, it is required to check Thrust value of the motor for desired current value. Looking at the Table 2 at 1060g Thrust value of the motor, the current drawn by the motor should be checked. This value is shown in the table as 7 A. The thrust value required for the UAV was calculated as approximately 1058 grams. Hence selected motor is suitable for our design and each motor is drawn 7A current in full load. These values have been taken into account by the technical analysis results on the 12 inch propeller. When the weight is added, the thrust value of the motor increases in the technical analysis results by increasing the propeller size. These results show that it can be solved by increasing the propeller size within the addition of parts to the UAV.

B. Battery Selection

Lithium ion battery is determined as the battery of the both UAV and the Rover. The reason for using a Lithium ion battery instead of a lithium polymer battery is that lithium ion has a high power density. Sony VTC 6 battery is used as battery. The output parameters of the battery were effective in this battery selection. Because the UAV needs a lot of firing power when taking off with its full load. This requirement has thus been solved. Each battery provides 3.7V and 3000mAh. Batteries were riveted to each other in the form of 6SP4 package. When the batteries are fully charged, a value of 22.2 Volts was obtained as output power. As a result, 12000mAh value and 22.2V values were provided by using 24 batteries in our design. On the other hand, as it is explained in the previous sub-section, 7A current will be enough. The advantage of the upper current value will be given in the next sub-section.

C. Calculation of Flight Time

The current value of the designed battery is 12000 mAh = 12 Ah. In order to calculate the flight time provided by the battery to the UAV, the following calculation steps are performed [14].

$$12A \times 60minutes = 720A \times minutes \tag{4}$$

Usually full engine efficiency cannot be achieved due to the losses. Universally 80% efficiency is achievable value for drone design. Hence,

$$720A \times minutes \times 0.8 = 576A \times minutes \tag{5}$$

The thrust value of the motor is based on 7 A. Because the value taken as a basis for weight corresponds to 7 A in this motor and we have total of 8 motors; current drawn can be calculated as;

$$7A \times 8 = 56A\ (total) \tag{6}$$

and total flight time of the UAV with full load can be calculated by using Eq.5 and Eq.6 as;

$$(576A \times minutes) \div 56A = 10,29\ minutes \tag{7}$$

It means, the UAV provides approximately 10 minutes of flight with full load with our design and selected equipment. Certainly by standby mode, operation time of the UAV will be longer.

D. Flight Controller of UAV

An UAV includes many electronic part additional to mechanical parts. The most important electronic part of an UAV is the Flight control card. A Flight control card is the circuit board that manages the flight of the UAV. The flight controller's job is to control the power, or speed (Rotates per Minute - RPM), for each motor on the UAV in response to the information received from the UAV controller. It receives raw information from the UAV controller transmitted through the receiver and then makes the corresponding movement to the UAV's controller. Since UAVs have multiple motors, the flight controller's job is to take the information sent by the UAV controller and then act on it so that each individual motor receives the appropriate amount of power to execute the requested movement.

When a flight controller is set up well, the UAV pilot's commands sent via the UAV controller should correspond exactly to how the UAV moves in the air. Pixhawk flight control card was used because it fulfils the desired objectives and is also octocopter compatibility. It supports 8 electronic speed controllers (ESC) and 8 motors. Technical accuracy in terms of use and interface is higher quality. The avionics system wiring diagram of flight control card is shown in Fig.4. The camera, router and other additional systems are connected to another battery separately from the flight systems.

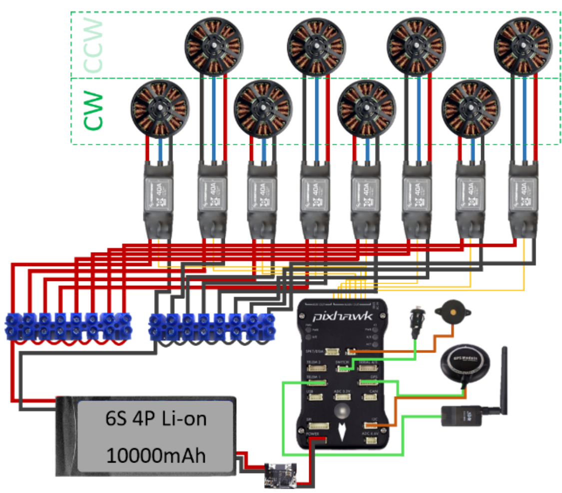

Fig. 4. The Avionics System Wiring Diagram.

E. PID Control Adjustments

To ensure a stable flight with and without load, the power of the each motor must be controlled instantaneously and the required adjustments must be done carefully and electronically as fast as possible. PID controllers are commonly used such adjustments reliably for UAV [15], [16], [17].

Adjusting to the UAV by using selected flight controller's (Pixhawk) user interface is a difficult process. The UAV needs to fly stable and hence, the most important factor is the tuning of the PID controller parameters. The Rover should not have any stability problems while flying with the UAV and weather conditions such as wind should be eliminated. For adjustment, all controller parameters are set to be zero and maximum values should not be exceeded. The operating point where the control card's performance is the best should be determined. There are 3 axes being Pitch(P) - axis, roll(R) - axis and yaw(Y)-axis. On the P-axis, the UAV tilts forward or backward. On the R axis the UAV tilts right or left. On the Y axis, it rotates counterclockwise and rotates from above in the maintenance direction [19]. Usually P, D, I settings are made respectively. Then yaw control is tuned for stability.

The P controller is proportional to the angle of inclination of the motor power. As the motor output changes, the UAV is tried to be stabilized. If the P value is high, the UAV starts to swing and if the P value is too low, the UAV is flying unsteadily. It is the best to increase the P value until the UAV begins to oscillate than this value is set. D value controls the reaction time of UAV by processing the sensor data. If D value is low, it will not act on the rapid changes. If it is too high, it starts to oscillate when sending less signal [18]. The I controller is used to change the current drawn by motor hence the power of motor. This changes the deflection angle, provides overall correction and balances against P and D controllers on the UAV. I value was kept as small as possible considering the P control. The designed and produced UAV can be seen in Fig.5.

Fig. 5. The Designed UAV.

F. Design of Rover

Rover is very important for functional purpose, and it should be very light in all aspects as well. First, the frame suitable for the purpose is selected. The Rover was designed in a 3D drawing area to suit the intended purposes. A tracked all-terrain vehicle was chosen in terms of lightness and tough terrain conditions. A motor that is as light and functional as possible was chosen for the Rover. This motor is 6V 250 RPM dc motor. Each crawler arm was positioned to have 2 motors. A clipper is added to Rover design to give extra ability for example destroy the bomb for Rover. MG90s servo motor is used in this robot arm. In Fig.6 the Rover and clipper can be seen. All plastic materials (blue and white parts in Fig.6) were produced with 3D printer.

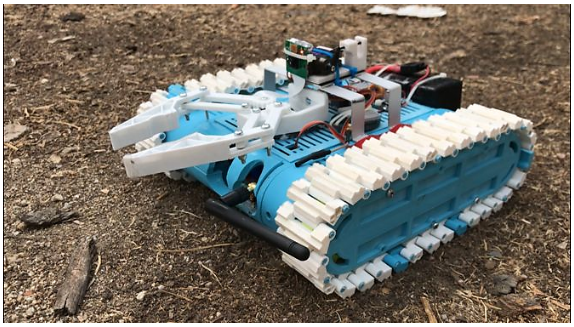

Fig. 6. The Designed UGV.

Rover includes 4 DC motors, L298N, Arduino UNO, nRF24L01 module, raspberry Pi, raspberry Pi camera module and 11.1 V battery. 4 motors are connected to l298n according to + and ground outputs. The nrf24L01 module was positioned on the Arduino UNO in line with the codes in the software. Appropriate connections to L298N have been made on Arduino Nano. Battery connected to L298N and raspberry PI module. Camera module is socketed to raspberry Pi. The Rover mechanism is completed as in Fig.6. Electrical connections can be seen in detail in Fig.7.

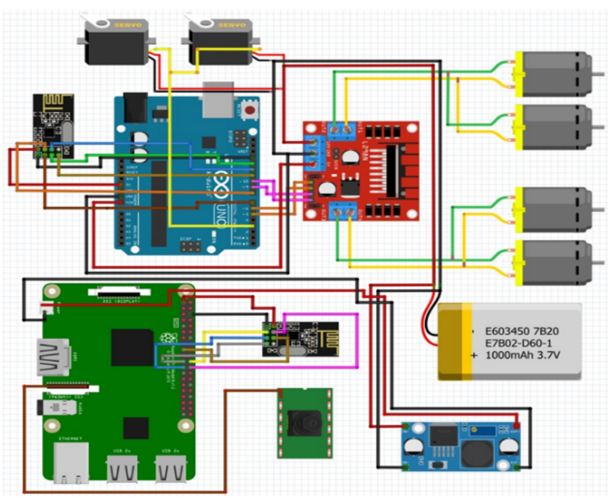

Fig. 7. Connections of Rover‘s Electronics Parts.

IV. Communication System

Nowadays, there are many protocols to be used for communication purposes. Concentrating on the necessary protocol according to the place and purpose of use always provides convenience. Therefore, the SPI Protocol was deemed the most appropriate for this project and studies were carried out on it.

A. SPI Protocols

SPI (Serial Peripheral Interface) is one of the synchronous serial communication types that Arduino supports. It is similar to I2C in terms of features and usage. It allows an Arduino to communicate with other Arduinos or sensors in a short distance. In SPI protocol, there is one Master device as in I2C. This device controls the connected peripheral devices. This is a very necessary condition for the targeted project. There are four SPI lines, MISO (Master In Slave Out), MOSI (Master Out Slave In) and SCK (Serial Clock), CS (SS) (Chip Select) which connect to the master and peripheral devices.

As can be seen from the MISO and MOSI lines in Figure 8, the data lines are unidirectional in the SPI protocol, unlike I2C. In addition, peripheral devices (slave) do not need to have addresses [19]. Each peripheral device has a selection terminal. This terminal is called Slave Select (SS) terminal. The number of this line is equal to the number of peripheral devices activated [20]. For each device, a separate SS line emerges from the master device. Peripheral device with SS line LOW (0 volts) starts communication with master device [21]. SPI communication example is shown in Fig.8. As can be seen in this figure, there are SS outputs from the Master device as much as the number of peripheral devices. The master device pulls the SS pin of the peripheral device it wants to communicate with to the LOW (0 Volt) level [22].

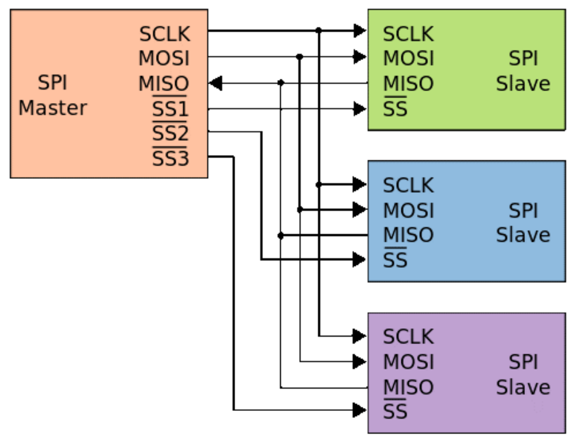

Fig. 8. An Example of SPI Communication Schema [22].

As can be seen in the Fig.8, the master part of the project is taken as the central control station. The antenna positioned on the UAV as the router and the Rover antenna, which is the end point, are operated as slave devices in our design.

B. nRF24L01 Communication Module

nRF24L01 is an inexpensive communication module that supports SPI communication protocol and has the necessary I/O pins, using the 2.4 GHz band. As mentioned before, SPI communication is an indispensable protocol for the Project. Therefore, this module is very advantageous for the project and it has been decided to use this module.

These modules are presented to the user in two types in the market. One of them does not contain an external antenna and is more suitable for close range use. The other antenna model, on the other hand, has few differences in design and has a high range in outdoor use. This module is called nRF24L01+ PA/LNA. The general structure of both models is shown in Fig.9.

Module with version without external antenna uses the built-in antenna and the other model has an SMA connector

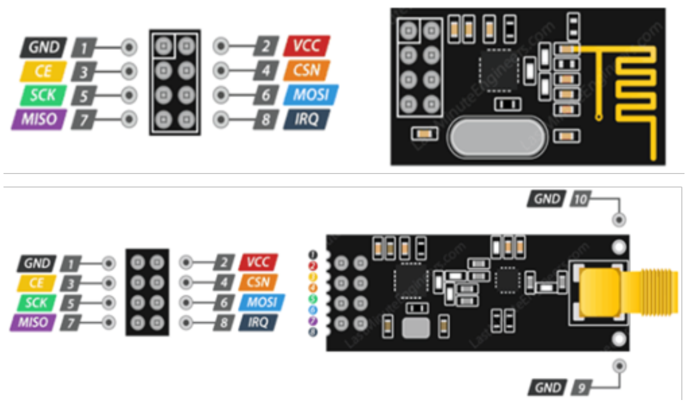

Fig. 9. General Structure of nRF24L01 Modules [23].

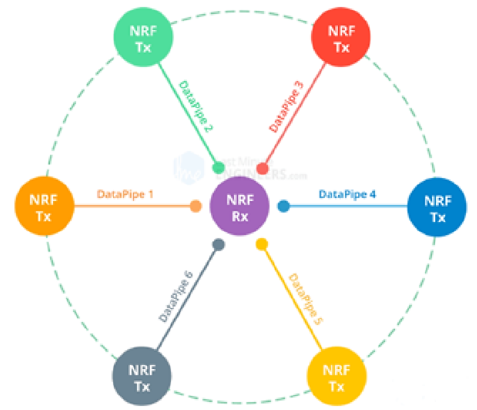

Fig. 11. Multiceiver Operation of nRF24L01.

and a duck antenna. For this project, the use of the model with an external antenna from these two models was deemed appropriate. The nRF24L01+ transceiver module transmits and receives data on a specific frequency, called a Channel, and two or more transceiver modules must be on the same channel to communicate with each other [23]. This channel can be on any frequency of the 2.4 GHz ISM band, or more precisely between 2.400 and 2.525 GHz (2400 to 2525 MHz).

It occupies less than 1 MHz of bandwidth for each channel, providing 125 different channels with 1 MHz spacing. In this way, the module can use 125 different channels, giving the opportunity to have a network of 125 different and independent modules in one place. Channel 115 was used for communication within the scope of the project. This channel division is shown in Fig.10.

The nRF24L01+ provides an extra feature called Multiceiver. This means multi-transmitter is operated with single receiver. Each RF channel is logically divided into 6 parallel data channels, called Data Pipes. In other words, it is a logical channel in a physical RF Channel, just like a data pipe. Each data pipeline has its own configurable Data Pipe Address. This can be demonstrated as shown in Fig.11.

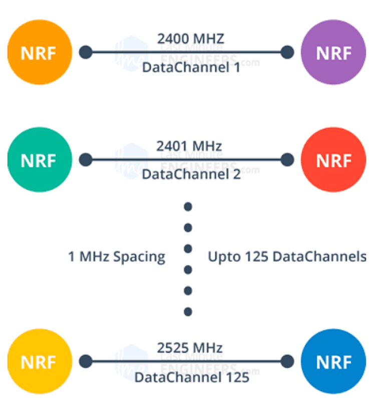

Fig. 10. Data Channel explanation of nRF24L01.

To explain the diagram above, the primary receiver is considered to act as a hub receiver, collecting information from 6 different transmitter nodes simultaneously. In this way, the Hub receiver can stop listening at any time and act as a transmitter. But during this process, it can only spawn one pipe/node at a time.

The nRF24L01+ transceiver module is designed to operate in the worldwide 2.4 GHz ISM frequency band, and the data transfer rate can be 250kbps, 1Mbps and 2Mbps. The operating voltage of the module is between 1.9V and 3.6V, but the good news is that the logic pins are 5 volt tolerant and can be easily connected to 5V without using a converter [24]. The module supports programmable output power. It consumes an incredible 12 mA at 0 dBm. And best of all, it consumes 26 µA in standby mode and 900 nA in power off mode which are very low. Therefore, they are wireless devices for low-power applications. Also, it supports the advanced ShockBurst^{TM} acceleration protocol [23].

C. End-Point (Rover) and Master (Control Station) Communication

The communication between the Rover Receiver, called End Point, and the Central Control Station is provided by the module on the UAV. The module on the UAV acts as a routing here. Therefore, it is named as Router. In short, the data from the Central Control Station was transferred to the endpoint via the router. Communication management is shown schematically in Fig.12.

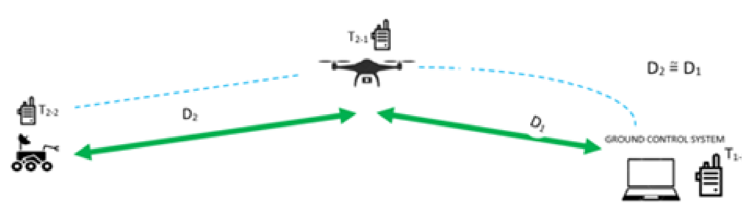

Fig. 12. Explanation of Whole Communication System.

D. Control Station (Master) – UAV (Router) Communication

This part is one of the important communication parts of the project. This communication takes place by communicating with the Central Control Station and the nRF24L01 module on the UAV, which helps to send the data and commands we give from the joystick to the UAV. This stage is the starting point of other communication, that is, the UAV acts as a bridge and transmits the parameter information it receives from the control station to the Rover. Conversely, the Rover transmits the collected data to the Central Control Station via the UAV. The electrical wiring diagram of the controller and controller of Rover is shown in Fig.13.

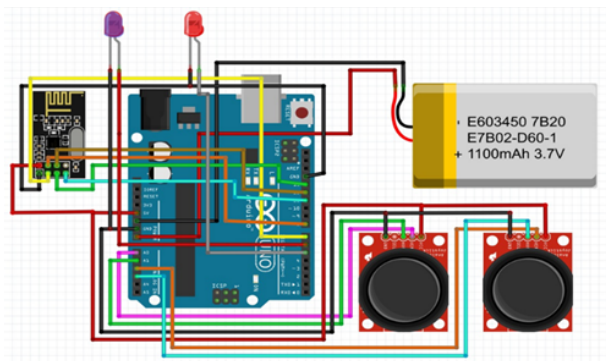

Fig. 13. Electrical Wiring of Controller.

The flowchart of the transmitter antenna module that acts as a transmission in the Central Control Station is shown in Fig.14.

E. UAV (Router) – Rover (End-Point) Communication

This connection between the UAV and the Rover, which is another important and main purpose of the project, in such cases as narrow areas where the UAV cannot reach the planned address, the range of the UAV alone is not enough and the battery is a problem, the desired operation can be carried out thanks to this communication. This communication is also provided with nrf24L01 modules. Thanks to this connection, the image and sound recording data collected by the Rover is first transmitted to the UAV and then transmitted to the Central Control Station via the UAV. Relevant codes are given in the conclusion section. The algorithm flowchart of the router antenna module that acts as a bridge network on the UAV and receive antenna module on the Rover is shown in Fig.15.

F. Communication Range Test

In the light of the designed algorithms, range tests were carried out in different scenarios. Two tests were conducted in areas with high building density (city) and in a completely open area with no buildings or obstructions. Usually the building or any wave absorbing structure is called communication interferences. Therefore, there was quite a lot of communication interference in the first test performed. For these reasons, substantially different results were obtained in the two cases. As it can be seen in Fig.17, the communication range from Central Control Station to UAV (as router) is 315m and the range between UAV and the Rover is 330 m. It is shorter than the range of open area as expected since there are a lot of interferences and obstacles between the communication modules.

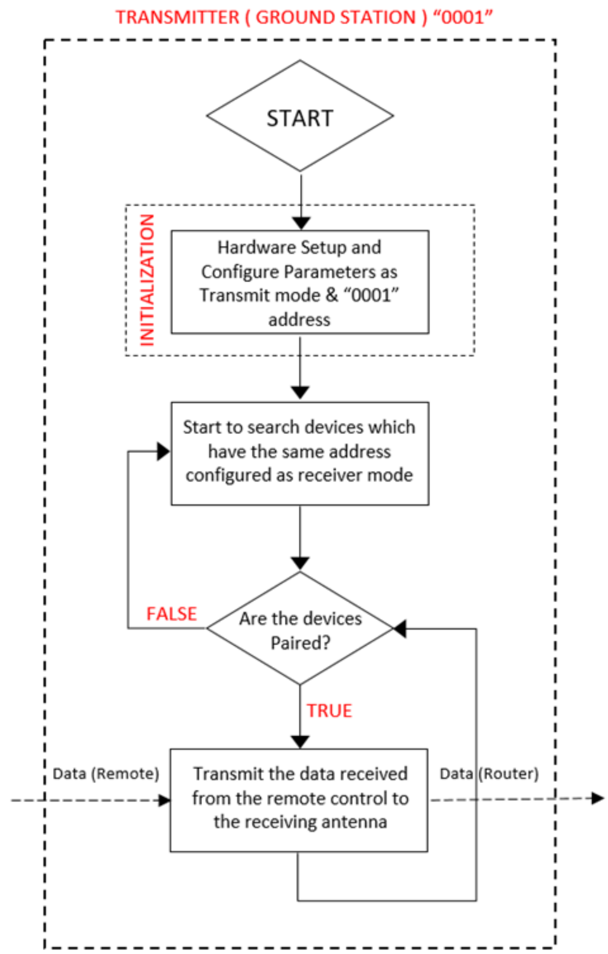

Fig. 14. Flowchart of Transmitter Algorithm.

The test results obtained in the open area have shown that the project can be used in practice and high ranges can be achieved with such an antenna in terms of budget. The open area test results are shown in Fig.18, and now it is clear that the communication ranges are increases as expected.

Now, the communication range from Central Control Station to UAV (as router) is 1480 m (instead of 315m) and the range between UAV and the Rover is 1520 m (instead of 330 m). We achieved the 5 times longer ranges in both. These results are summarized in Table III.

TABLE III
MAXIMUM OBTAINED COMMUNICATION RANGES BETWEEN THE UNITS.

	Ranges, m		
Region	**CS - UAV**	**UAV - Rover**	**Total**
Urban	315	330	645
Rural	1480	1520	3000

It has been seen that the designed system doubles the range between Central Control Station and the Rover which is the main idea of this paper. On the other hand, these are two-way communications between the units as well. The footage of camera on Rover is transferred to the Central Control Station

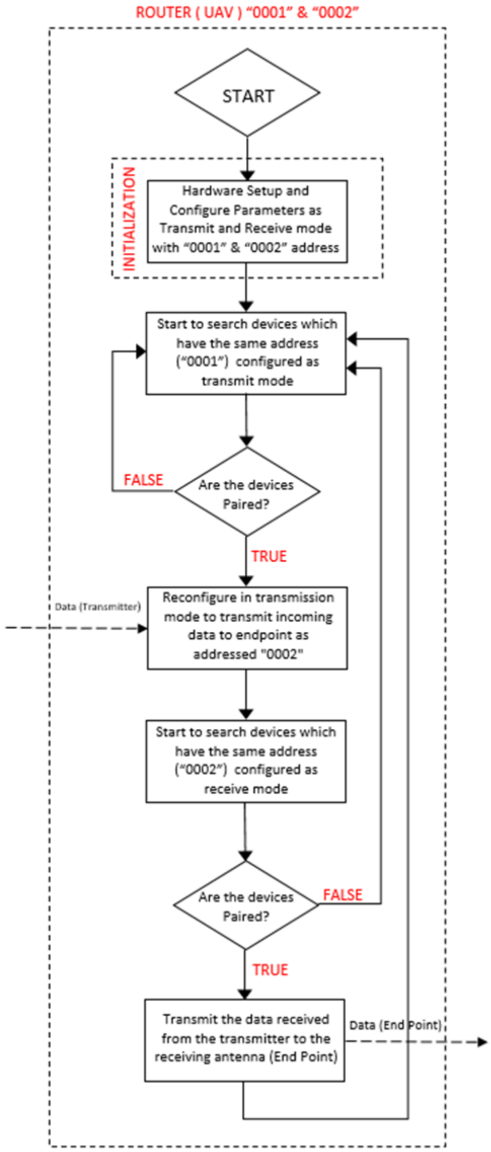

Fig. 15. Flowchart of Router Algorithm.

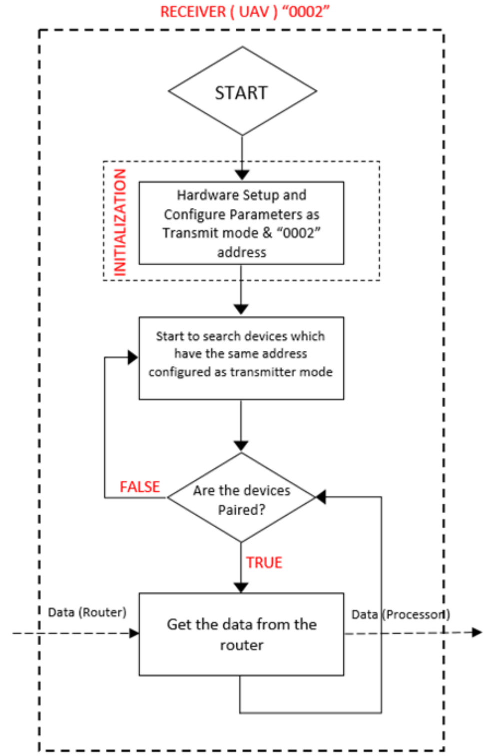

Fig. 16. Flowchart of Receiver Algorithm

Fig. 17. Urban Communication Test Result.

with some delay. Delay amount is proportional with the range and it is acceptable for critical missions.

V. Conclusion

In this paper, two-way communication system in between ground station and a ground vehicle over a UAV is designed and implemented with commercial and cheap microcontrollers, transceiver modules, flight controller, motors, sensors and 3D printer. The most difficult problem is the 2-way communication of the UAV as a router between the two modules (Central Control Station and Rover) at the same time without losing information. There are some delays in the 2-way communication between the units, but these delays can be further decreased with the selection of the superior microcontrollers and transceiver modules. Certainly this will increase the cost of the system.

Another important and critical problem to be solved is ensuring the stable flight for UAV with full load. Flight stabilization has been fully ensured and PID control algorithms have been developed successfully. The Rover, which will serve with the UAV, has been successfully implemented and fulfilled the tasks given in the real environment. With the established relay communication, many problems are solved. The release mechanism of Rover is fully provided. The UAV will leave the Rover exactly where the Rover will work. As stated before, the communication range has been tested under the influence of interference and without being under the influence of interference, and it is shown that communication range is doubled with this system.

The generated codes, circuit schematics and all required data to reproduce this project can be obtained from the following address;

https://github.com/irisuavgithub/Spy-Drone-Project—Relay-Communication-System-with-nRF24L01-

Fig. 18. Open Area (Rural) Communication Test Result.

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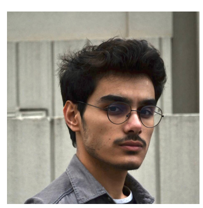

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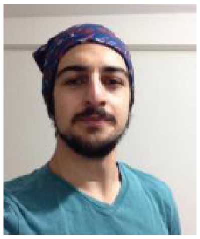

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