Exploiting the Use of Unmanned Aerial Vehicles to Provide Resilience in Wireless Sensor Networks

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The authors would like to acknowledge the financial support granted by FAPESP (São Paulo State Research Foundation, processes 2014/06330-5 and 2012/22550-0), CNPq (Brazilian Research Council, processes 473493/2013-6 and 132007/2013-4) and Capes (National Council for the Improvement of Higher Education, process DS-6706658/D). Jó Ueyama would also like to thank the Office of Naval Research Global for funding part of his research project.

ABSTRACT

A wireless sensor network is liable to suffer faults for several reasons, which include faulty nodes or even the fact that nodes have been destroyed by a natural disaster, such as a flood. These faults can give rise to serious problems if WSNs do not have a reconfiguration mechanism at execution. It should be noted that many WSNs designed to detect natural disasters are deployed in inhospitable places and depend on multihop communication to allow the data to reach a sink node. As a result, a fault in a single node can leave a part of the system inoperable until the node recovers from this failure. In light of this, this article outlines a solution that entails employing unmanned aerial vehicles to reduce the problems arising from faults in a sensor network when monitoring natural disasters like floods and landslides. In the solution put forward, UAVs can be transported to the site of the disaster to mitigate problems caused by faults (e.g., by serving as routers or even acting as a data mule). Experiments conducted with real UAVs and with our WSN-based prototype for flood detection (already deployed in São Carlos, State of São Paulo, Brazil, have proven that this is a viable approach.

INTRODUCTION

Although in many cases natural disasters cannot be avoided, their effects can be mitigated through issuing warnings and following suitable rescue procedures. In the period following a disaster, the monitoring of affected areas is of vital importance to prevent dangerous measures being taken and to safeguard human lives. With this aim in mind, we have developed and deployed a wireless sensor network (WSN) for urban river monitoring, which is described in details in [1]. Briefly, WSNs are distributed systems composed of sensors that are interconnected through wireless links. They are used to monitor physical phenomena such as temperature, atmospheric pressure, and light exposure for various purposes in, for example, medical, civilian, and military areas. Its form of communication is carried out through multiple hops where nodes communicate with their neighbors until the data reach their final destination.

Our WSN-based system monitors river floods, and issues warnings to the population and vehicles at risk. To date, we have constructed and deployed eight sensor nodes in the city of São Carlos in São Paulo, Brazil. The urban rivers in the city of São Carlos have an elongated shape, and hence the sensors were deployed linearly along the river (Fig. 1). Urban rivers in Brazil are usually surrounded by big roads such as the so-called Marginal Tietê in São Paulo. In São Carlos, there is the Marginal Tijuco Preto road. As a result, these roads tend to get flooded, which means there is a need to send warnings to drivers to avoid those areas when they are at risk.

Since the sensor nodes are deployed linearly, we have adopted ZigBee multihop communication, which enables each node to send its packets to its neighbor toward the sink node. Clearly, the failure of a node will compromise the WSN either completely or partially. In particular, a couple of sensor nodes may be washed away during a flash flood, causing damage to the whole system. We have devised a number of fault tolerance mechanisms to ensure robustness and resilience, including the use of a third generation (3G) network in case the multihop transmission fails. Obviously, not all the sensor nodes have a 3G network as a way of providing a lighter prototype. In this scenario, a couple of sensor nodes with a 3G network may be destroyed, and/or the 3G network might not be operating during the period of a critical flood.

As a result, we propose the use of unmanned aerial vehicles (UAVs) to make the WSN more resilient to failures and natural disasters that our river monitoring WSN is prone to suffer. UAVs are used for various tasks, whether they are civil-

The e-NOÉ employs a pressure sensor to undertake this work because one of the basic principles of physics is that the degree of pressure exerted at a particular point within the river depends on the height of the water column above it.

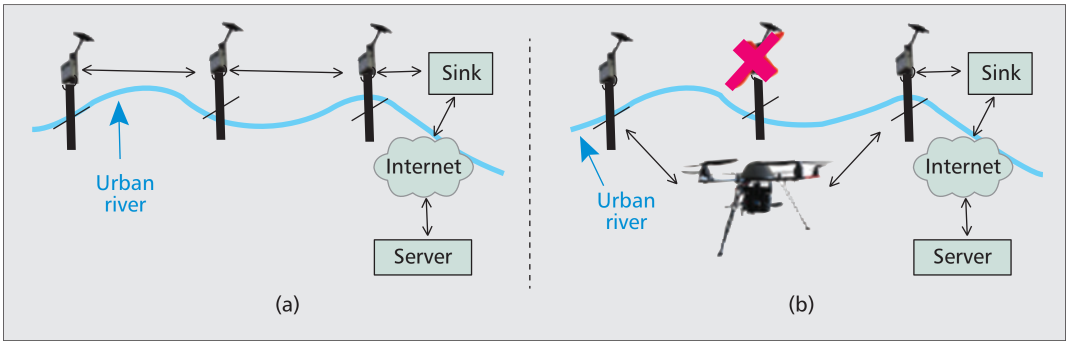

Figure 1. When the WSN is in normal operation mode, the messages with information about the monitoring of the urban river are transmitted over multihop to the sink node: a) the sink node sends all the information to a central processing unit through an Internet connection; b) when a failure occurs in a sensor node, previous nodes cannot transmit their data to the sink node. Since this part is without communication, it remains temporarily inoperable until the failed node has been repaired or connection re-established. By employing our prototype of the mobile node, it is possible to re-establish the connection or collect data throughout the WSN and convey it to the processing center. This choice is carried out in accordance with the plan of action used.

ian or military, including surveillance, reconnaissance, monitoring, and aerial mapping. Another area where UAVs can be employed is to maintain connectivity with a WSN if there are failings in the infrastructure. In our proposal, the UAV Microcopter (an unmanned mini-helicopter with eight propellers) can be employed in two key capacities: i) to act as a router in case a node fails to transmit packets in multihop communication (Fig. 1); and ii) to serve as a data mule [2] for data dissemination, which can help us to form a delay-tolerant network (DTN) in which packets from our WSN can be disseminated to a vehicular ad hoc network (VANET) so that drivers can avoid flooded roads

To show the feasibility of our proposal, an investigative study of wireless communication has been undertaken between terrestrial sensors and the UAVs. The key feature of the analysis is an assessment of the electric power consumption of the wireless communication device, which is fitted to the UAV at the network response time and in the packet losses.

The remainder of this article is structured as follows. We outline related work in the field. We explain the approach that has been adopted. We give a detailed account of the experimental environment. We include a discussion of the results of the experiments, and we summarize the conclusions of the authors about the results of this study.

Related Work

Although there are works such as [3–5] that propose the use of UAVs to integrate WSNs, it was noted that there are no studies that investigate the use of UAVs as a gateway and data mule, or include an analytical study of energy consumption. Moreover, only a few of them use the ZigBee protocol, which is the most widely used standard for WSNs and the focus of our study.

The aim of the study by Hauert and colleagues [3] was to set up a communication network in disaster areas through UAVs. The project employs UAVs to spread out the nodes of a network in a disaster zone with the aim of establishing communication with rescue teams. Some real UAV prototypes were constructed with modules from a global positioning system (GPS) module and a ZigBee transmitter.

The main proposal of Freitas and colleagues [4] is to recommend the use of UAVs to give support/connectivity to the WSNs installed on land. The principal feature is to investigate an attempt to provide connectivity between the UAVs and the subnetworks formed by the WSN nodes on the ground. In carrying out this study, the authors assume that the WSN network was abstracted, and the study is focused on the way the UAVs operate.

The study by Tuna and colleagues [5] outlines strategies for the use of UAVs in implementing a WSN for monitoring a post-disaster recovery phase. These strategies involve determining routes, making improvements to positioning, and finding better sites for placing the wireless sensors. The proposal uses UAVs to spread out wireless sensors in the area coverage of the WSN network. The proposed system was simulated with USARSim to assess the location and navigation performance of a UAV responsible for the layout of the WSN. The study does not specify what kind of wireless technology was used.

As mentioned earlier, the use of a UAV to integrate the UAVs and WSNs is indeed not novel, and there are a few works that address this issue. Our group has just published a paper[1] that outlines the use of UAVs and WSNs for detecting pesticide drifts while spraying chemicals on crop fields. Having said that, it should be stressed that none of the works make use of UAVs to provide a higher degree of resilience for WSNs to act against natural disasters (e.g., floods) or make evaluations based on real devices. For this reason, our work includes real experiments that involve both prototyped UAVs and deployed WSNs (i.e., our work does not include validation through a simulation tool). The tested UAV was equipped by our group with a Zigbee transmitter and a Raspberry Pi so that our communication evaluations could be conducted with the deployed WSN.

[1] B. S. Faiçal *et al.*, "The Use of Unmanned Aerial Vehicles and Wireless Sensor Networks for Spraying Pesticides," *J. Systems Architecture*, vol. 60, no. 4, 2014, pp. 393–404.

The Proposal

This article seeks to show how mobile nodes are capable of providing resilience to a WSN employed for urban river monitoring. The WSN obtains information about the behavior of the river and transmits it to a central processing unit where it can be used for predicting a possible flood. In addition, we have constructed a real prototype and conducted an exploratory analysis of the energy consumption of a UAV and sensor nodes (without the help of a simulation tool). A sensor node that is able to communicate with the WSN deployed in the area of interest (on the bank of an urban river) is coupled to the UAV, and thus makes a mobile node. This node is used when a fault in the WSN makes part of the network inoperable. Although an alternative strategy is to add nodes to the network to increase fault tolerance/resilience, this solution shortens the battery life because it increases the amount of data being transmitted, as well as the cost incurred by the duplication of equipment and deployment. Additionally, this solution does not guarantee fault tolerance/resilience due to the prevailing environment conditions at the time of the disaster. On the other hand, the use of a UAV to provide resilience in the WSN adds some important extra features, such as:

- The UAV can be equipped with a camera to transmit images in real time for rescue teams.
- It can act as a data mule between the points separated by the communicating nodes.
- It can map out the affected disaster areas while performing other activities.
- Unlike vehicles (of the rescue teams), it can navigate over rivers, creeks, and areas affected by floods, landslides, and earthquakes.

In light of this, our UAV will perform two key roles:

- To serve as a router in multihop transmission. While it is unable to last for a long time, we still argue that the critical information will arrive in a timely manner for the population and during the lifetime of the UAV battery. UAVs can also send images (taken by themselves) to rescue teams so that they can mitigate natural disasters such as floods and landslides.
- To act as a data mule. This will help us to construct a DTN-type network. The data about the river, such as its depth level, can be conveyed and subsequently downloaded to the network infrastructure such as that of VANETs. This can be integrated to several existing data dissemination algorithms for VANETs such as the [6].

Figure 1 shows a WSN that is deployed at the edge of an urban river to monitor the behavior of the water flow. The prototype was deployed at this location due to the frequency of the floods there, particularly during periods of torrential or prolonged rainfall. It is thus possible to observe the standard operation of the WSN (Fig. 1a). The messages with information about the urban river are transmitted through multihop to the sink node so that the information about the entire WSN can be sent to the base station. However, WSNs are subject to failures, and this problem renders part of the architecture inoperative, since it cannot transfer the data that has been monitored. Nevertheless, with the use of a UAV acting as a mobile node (Fig. 1b), the new architecture can provide a higher degree of fault tolerance for the entire model.

Predicting Floods: e-NOÉ

A WSN consists of a set of sensor nodes used in an area of interest to monitor different phenomena (e.g., temperature or light exposure) [7]. These sensor nodes can operate as relay networks (repeaters in a wireless network employed to transmit data to a destination outside the transmission range). Each sensor node is basically composed of four units: a sensing unit, a processing unit, communication, and power supply [7, 8]. There are various research studies that employ WSNs [9–11]; prominent among these are studies for the monitoring of urban rivers with the aim of forecasting floods [10, 12].

Our project for monitoring urban rivers is called e-NOÉ, and one of its aims is to detect and predict floods with a view to being able to issue warnings, and avoid serious damage and loss of life. The sensing component in the e-NOÉ project (also called a node) is fitted with sensors (e.g., for pressure and temperature), and these are installed at strategic points along the banks of a river. They are connected to each other through a wireless network. The nodes communicate with each other with the aim of establishing a link with the base station that is responsible for the conversion of the networks.

The e-NOÉ employs a pressure sensor to undertake this work because one of the basic principles of physics is that the degree of pressure exerted at a particular point within the river depends on the height of the water column above it. With a pressure sensor it is easy to measure the height of this column. A sudden increase in the height in a short period of time indicates signs of a possible flood; warnings can then be sent to the people who are in the areas of risk.

The Prototype of a Mobile Node

UAVs are airships that are either capable of carrying out flights autonomously or remote controlled by a base station. This means it is not necessary to have pilots aboard during operations. These airships can undertake various activities in situations of high risk for humans or in areas where it is difficult to obtain access. Compared with conventional airships (flown by pilots aboard), the UAVs offer a safe alternative for various applications at a low cost [13, 14]. The UAVs have a wide range of technological devices that can be of assistance during the flight such as flight controllers, an onboard computer, GPS modules, and sensors. In addition, the UAVs are equipped with wireless communication resources that are able to exchange information with other features of a data network. In this scenario, the UAV becomes a mobile node of this data network.

Two large categories of the various UAV models are worth highlighting and can be classified as follows:

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Figure 2. Our prototype has the sensor node located in the undercarriage and involves the following items: a) the ZigBee wireless communication module; b) Arduino, used to monitor the power consumption of ZigBee and UAV; c) Raspberry, the computational component of the sensor node; d) the Power Meter Shield, connected to the Arduino and assisting in monitoring the power consumption of ZigBee; e) the temperature and humidity sensors providing basic information on weather conditions; f) the antenna coupled to ZigBee.

- Fixed-wing UAVs — These have a design like traditional planes where the vehicle support is obtained through wings that are fixed in line with the fuselage.
- Those with rotary wings — These are helicopters where the vehicle support is obtained through the wings (propellers), which move in line with the fuselage.

The rotary wing UAVs possess features that are closely linked to the objectives of this study. The ability to take off and land with vertical guidance allows the prototype to initiate and finalize its flights in environments where the ground is irregular. In addition, these models can hover and need less aerial space to carry out maneuvers than fixed-wing UAVs. These features provide a prototype with greater flexibility. Figure 2 shows details of our prototype.

In our prototype, we developed a module that is responsible for the entire communication between the UAV and the WSN, which is located in the undercarriage (Fig. 2). Thus, the prototype has become a mobile node that is able to route messages with the aim of overcoming obstacles (e.g., it acts as a bridge to boost the signal range so that it can address the problem of failures in any fixed sensor node), and it can also be employed as a data mule (e.g., by collecting data from the WSN and sending it to the central processing unit).

Performance Evaluation

An experimental environment was created with the aim of obtaining more reliable data[1] for the experiments. Three agents were used in this scenario: i) the client, ii) the UAV, and iii) the server. The client is responsible for making the requests to the server, as well as coordinating the UAV activities. The UAV carries out the role of routing the packets between the client and the server as well as monitoring the energy consumption of the ZigBee radio module. The server is responsible for replying to requests made by the client.

Three response variables were used for the performance evaluation:
- Energy consumption, for determining how much is being consumed by the ZigBee communication module
- Round-trip time (RTT) delay, which shows the transmission time from the transmitter node to the receiver node when passing through the UAV
- The packet loss rate, which represents the percentage of packets lost during the transmissions

The set of primary factors summarized in Table 1 was selected with the aim of conducting a performance evaluation of the UAVs. In carrying this out, the proposal is evaluated by means of a UAV (both on the ground and in flight), different distances (30 and 80 m) and different antenna gains (3 and 10 dBi). A complete factorial design was employed to enable every combination of the sets of factors to be put into effect. Each set of experiments was replicated 33 times, and a statistical comparison between the sets were carried out by employing the Shapiro-Wilk normality test and the Wilcoxon rank sum test.

Other relevant information gathered during the flight that influenced our performance evaluation is as follows:
- ZigBee channel: 16
- Room temperature: (26.98 ± 0.07) °C
- Relative humidity: (52.15 ± 0.11) percent
- Readings for the rate of energy consumption: 170 readings/s
- ZigBee communication rate: 9600 b/s
- ZigBee transmission power: 10 dBm

Energy Consumption of the Sensor Nodes

The energy consumption with regard to antenna gain and distance can be seen in Fig. 3a. It should be noted that the lowest confidence interval obtained occurred when the UAV was in flight (experiments E5 to E8), which shows a concentration of energy consumption close to the average ~ 2.38 mJ. Larger dispersion was obtained when the UAV was on the ground (experiments E1 to E4). Hence, the wireless communication performance is better when the node is further away from the ground. Information about this is obtained through the propagation of radio waves in the atmosphere, and it is influenced by reflections from the terrestrial soil [15]. It can be concluded that there is a reduction of energy consumption in the ZigBee communication module when the UAV is in flight.

Energy Consumption of the UAV

Figure 3b shows a sample with different conditions for the energy consumption of the UAV in flight. These conditions, when divided into regions, are described and discussed as follows:
- *Flying over with low wind*. The observed condition in this area is caused by an air passage. We detected a period of instability from the time when a current of air came into contact with the Microcopter. This is offset by an increase in torque and hence

[1] Data of the experiments are available at http://goo.gl/glUjUh.

the rotation of engines. This situation results in an increase in the energy consumption of the system.
- *Flying over with no wind — an ideal condition for the Microcopter*. In the ideal condition, the Microcopter tends to keep a state of equilibrium and only has to maintain a fixed altitude. In this case, a reduction in the power exerted by the engines can be observed; hence, there is a decrease of energy consumption.
- *An increase in the rotation of the motors to reach a higher altitude*. A considerable dissipation of the power of the motors is required for a sharp rise in altitude. As seen in Figs. 3b and 3c, this maneuver produces peak power.
- *Turning off the engines*. By default, when the motors are turned off, they suffer from an increase in speed, which causes a slight variation in power output.
- *Engines off*. In this situation, the power dissipated by the engines is minimized.

Round-Trip Time Delay

Figure 3c shows the results of the RTT with regard to the type of antenna and distance. It should be noted that the results are statistically equivalent for all cases observed (p-value above 0.05, Wilcoxon rank sum test). The extreme values shown in the RTT results follow a logical pattern since the environmental conditions are unsuitable and there is interference caused by the signals; the reason for this is that WiFi and ZigBee [16] use the same unlicensed frequency band of ~2.4 GHz. Different studies have shown that this feature affects the performance of ZigBee. In the analysis of extreme values, values higher than ~450 ms were not taken into account. It can be concluded that there was no loss or gain to the transmission times in the observed conditions.

Packet Losses

The results of packet losses were 0 percent lost packets for all eight experiments conducted (E1 to E8). It is thought that this was due to the data transfer rates employed. The transfer rate for wireless transmissions was 250 kb/s, and the transmission rate between the ZigBee and the computer was 9.6 kb/s, which was 26 times slower.

Discussion

In accordance with the aims of this article, the prototype showed it could provide mobility for the support node during the experiments in an appropriate way. The sensor node was able to temporarily replace the faulty sensor node in communicating with other sensor nodes without causing delay or packet loss. Moreover, these results suggest the need for a configuration with a more powerful antenna because this can provide a greater communication range and lower power consumption when away from the ground.

On the other hand, the power consumption of the UAV indicates the need for an action plan where the prototype is used as a data mule; in other words, to collect data on the inoperative party and transport them to a central processing unit. It should be noted that the prototype does not have to fly over the exact area where the sensor nodes are fixed, since it may be possible to use an antenna with a longer range. This plan of action has another positive aspect: the prototype often returns to the processing unit, which means its battery can be charged when necessary.

Experiments	Sensor node	Distance	Antenna gain
E1	Ground	30 m	3 dBi
E2	Ground	30 m	10 dBi
E3	Ground	80 m	3 dBi
E4	Ground	80 m	10 dBi
E5	Flight (5 m)	30 m	3 dBi
E6	Flight (5 m)	30 m	10 dBi
E7	Flight (5 m)	80 m	3 dBi
E8	Flight (5 m)	80 m	10 dBi

Table 1. The set of primary evaluated factors.

One drawback of the developed network is its bandwidth, since it operates by relying on ZigBee technology. The network has a data rate that is limited to the ZigBee communication rate, which is at most 115,200 b/s. With this transmission rate, it is not feasible to transmit creek/river images, which is why our network mainly transmits text data (i.e., no images are sent out through the ZigBee network). However, the use of the ZigBee radio is recommended for the context of our application, since it is a radio transmitter with long range and low power consumption.

Finally, it is worth remembering that this methodology seeks to explore the energy consumption of sensor nodes of WSNs used to predict floods and validate the proposed prototype of the mobile node. In this way, it can lead to the development of an action plan aimed at providing resilience for this architecture.

Conclusion

This article outlines the use of UAV as a means of providing robustness and resilience for wireless sensor networks. We conduct a review of related work and discuss the literature in the field. We also outline our proposal and the two key roles that the UAV can play in the event of node failures with our existing WSN. Experiments were carried out with a real UAV and an existing sensor node for river monitoring. Our WSN prototype is able to detect and predict; but when it is deployed in critical areas (i.e. where floods take place), it becomes highly prone to natural disasters, such as a flood itself.

In carrying out its task as a router in a WSN, the UAV has proven effective in terms of energy consumption, which makes it suitable for operating in controlled flight conditions and thus ensures the effectiveness of network operations in applications for flood detection. We conducted experiments with RTT to measure vertical transmission time from the UAV to sensor nodes. This is of particular interest when using UAV as a data mule. In addition, we ensured that the RTT times did not undergo variations in vertical transmission flow and the eight propellers of the UAV. We also made sure that there were no packet losses, so that the reliability features of ZigBee for the use of applications such as the e-NOÉ WSN-based river monitoring system could be validated.

To recap, our work included real experiments with both a prototyped UAV and a deployed WSN for flood monitoring (i.e., our work does not include validation through a simulation tool). In addition, it is important to point out that the tested wireless communication technology was able to transmit packets under an adverse condition (i.e., torrential rain). Due to that, the deployed WSN could predict three floods in the city of São Carlos. Our UAV was equipped with the same wireless communication technology; therefore, we believe that our UAV can help us to restore broken wireless communication and also serve as a data mule for providing a WSN with a higher degree of resilience against disasters.

The next stages of this project will be as follows:

- Other antennas with different ranges will be evaluated to minimize the route of the prototype.
- Evolutionary methods will be employed for route planning of action missions for a prototype that can be used as a data mule.
- The prototype will be evaluated in different weather conditions.

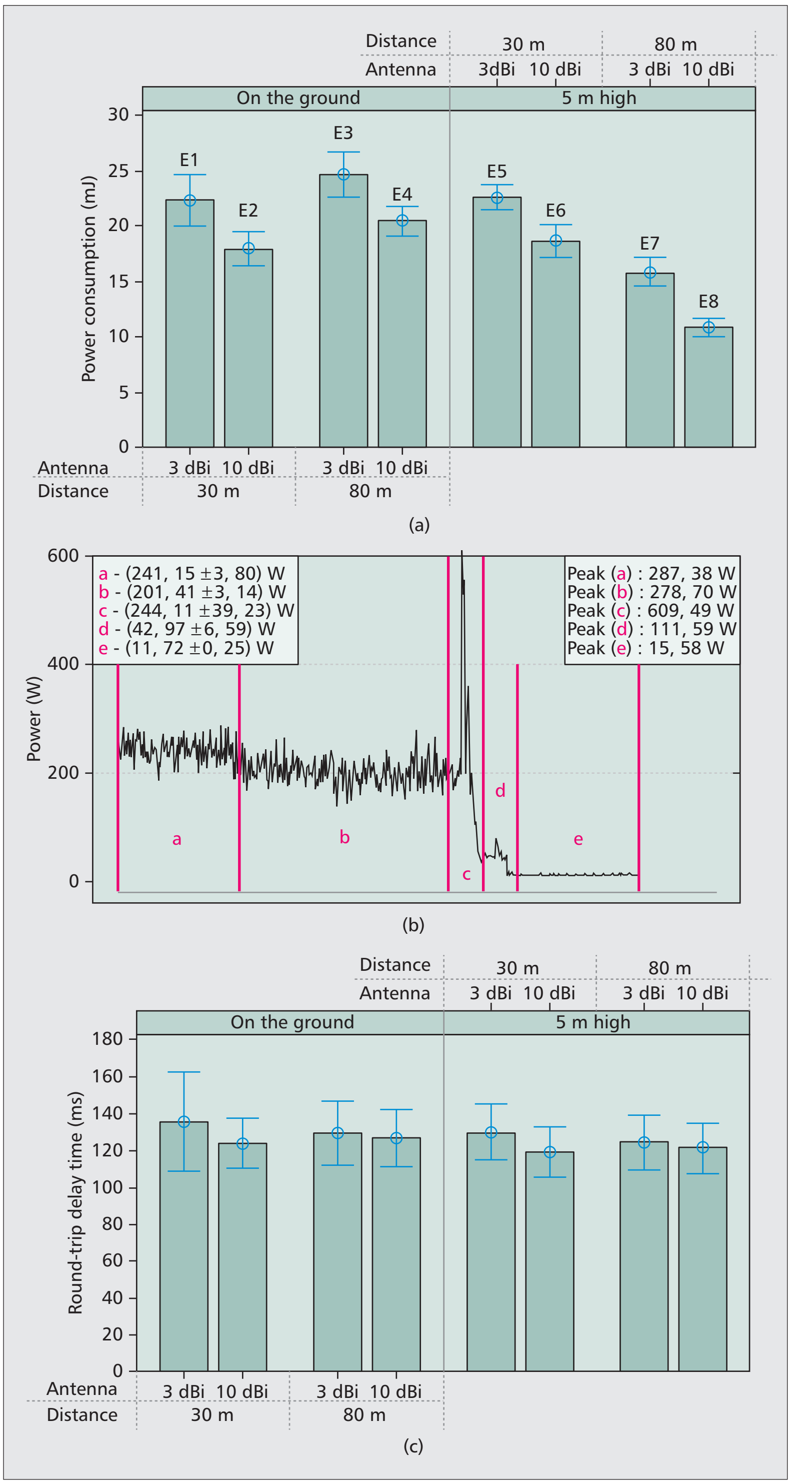

Figure 3. Results: a) energy consumption; b) power consumption of UAV during real flight; c) RTT delay.

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