4G Antipode: Remote Control of a Ground Vehicle From Around the World

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***Abstract*—Remote control of vehicles (in the air, on the land, and on the sea) is usually performed with a custom radio link. However, with the prevalence of cellular networks, command and control via 4G cellular networks is possible. In this work, we demonstrate control of a remote-controlled vehicle at two points on the Earth that are almost the antipodes (opposite sides of the Earth), at a distance of 18 500 km apart. A remote video link is also provided. This demonstrates the longest distance yet of control of a vehicle via a 4G cellular link.**

***Index Terms*—4G, autonomous vehicle, drone.**

I. INTRODUCTION

REMOTE-CONTROLLED vehicle technology with local onboard intelligence of various degrees of autonomy is developing at a rapid pace. This includes all classes of vehicles on land, air, and sea: ground-based vehicles (self-driving cars, trucks, and rovers), aerial vehicles (drones, UAS, etc.), and even water-based vehicles. Internet-based (including cellular) control is a versatile potential method, and with the prevalence of cellular data plans, offers an economical, flexible, and broadly based communications technology with the potential to control fleets of cars, trucks, drones, boats, etc.

In this work, we demonstrate IP-based (using a 4G cellular network) command and control of a semi-autonomous rover-based ground vehicle from two points on the Earth separated by 18 500 km (Fig. 1), close to the maximum distance of 20 000 km (antipode). This article is a "proof of concept" paper, not a quantitative technical analysis of long range delay. An accompanying paper details more quantitatively the video delay and technical description of the platform [1]. This proof of concept demonstrates the advantage of low cost usage of the communications infrastructure built up over the last 20 years for truly global integration of vehicle networks. As such, it lays the groundwork for an integrated, fleet wide global network of vehicular technology.

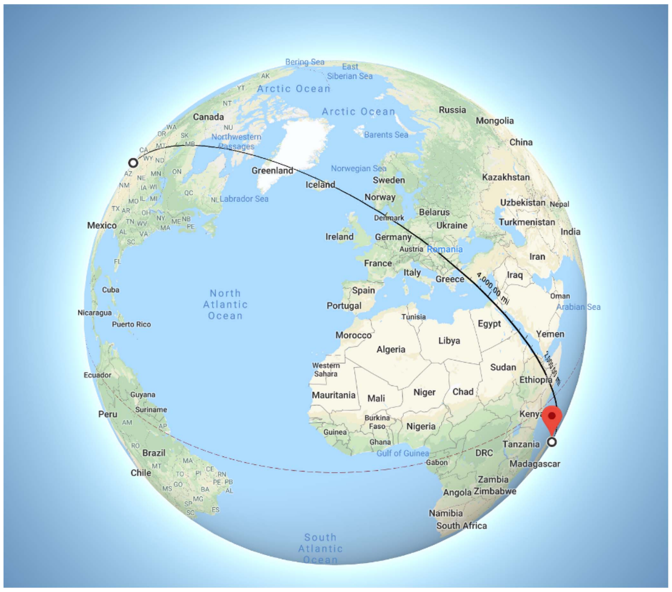

Fig. 1. Google Earth plot of the distance between command and control location (Reunion Island, off the coast of Madagascar), and the autonomous ground vehicle location (Southern California). The distance between the two points is 18 500 km.

II. BACKGROUND

A. Problem

The problem of long range command and control is that the radio links are limited by the available transmit power, the Friis propagation loss, and the receiver noise floor. This limits practically RF control links to the order of 10 km.

B. Previous Solutions and Their Weaknesses

Previous solutions have used higher RF power, or lower bit rate, to achieve longer range command and control. Higher RF power incurs a greater cost and is limited by FCC and similar regulations as well as safety. The lower bit rate makes the use of manual control and video challenging.

C. Proposed Methodology

The proposed methodology leverages billions of dollars of investment in communications infrastructure and the open low cost nature of IP transport protocol to enable long range command and control. The demonstration at high size scales

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(typically several kg) with drones was reviewed by us in [2] but has not ever been demonstrated at this size scale for rover technology as we do here.

III. PLATFORM TECHNOLOGY

The platform technology is based on a 4G Internet control first described in [2] for a flying wing. The platform was then transplanted into a ground vehicle as demonstrated in [1]. Therefore, the platform, while used for a specific vehicle and type, is versatile and general purpose.

A. Vehicle

The vehicle is an electric powered rover, with a length of about 27 cm.

B. Control Electronics: Hardware

The control electronics includes an STM32-based microcontroller with UART and IC2 ports for GPS, RF link, and companion computer interface. The controller sends servo signals to the throttle and steering. The companion computer is a Raspberry Pi with separate digital camera. A Novatel modem connects the Raspberry Pi to the cellular data network with a 4G connection.

C. Control Electronics: Software

The control software is Arudpilot Rover v 3.5.2. The remote pilot control station is Windows 10 instance (see below) running Mission Planner.

D. Command and Control Link

The 4G command and control link uses the MavLink protocol to send commands over the Internet. The main architecture was already described in [1] and [2], where a Windows 10 machine was connected over the Internet to the vehicle for command and control.

In this case, a slightly revised architecture was used: since the Windows 10 to Internet connection may be blocked by firewalls, a cloud-based virtual instance of Windows 10 machine was used. This is the first cloud-based ground control system ever used, to our knowledge, described next.

1) Cloud-Based Control Station: Using the Arudpilot software, under GPS control, the vehicle can pilot itself from waypoint to waypoint. In order to demonstrate around-the-world control, a virtual Windows 10 machine running Mission Planner was spun up in the cloud. Because Amazon is the only cloud provider that enables a Web browser interface to a virtual Windows machine (even Microsoft's Azure platform does not provide this), the virtual machine was run on the AWS server platform. A Web browser was used to log into the Windows virtual machine and run Mission Planner. From within the Windows virtual machine, appropriate SSH tunnels were secured between the vehicle's onboard Raspberry Pi and the Windows virtual machine, as described in www.gitlab.com/pjbca/4GUAV, [1], and [2]. This enabled the use and testing of the platform locally to ensure only a Web browser would be needed for the command and control, in case of any firewall issues when on the remote island of Reunion. The architecture is shown in Fig. 2.

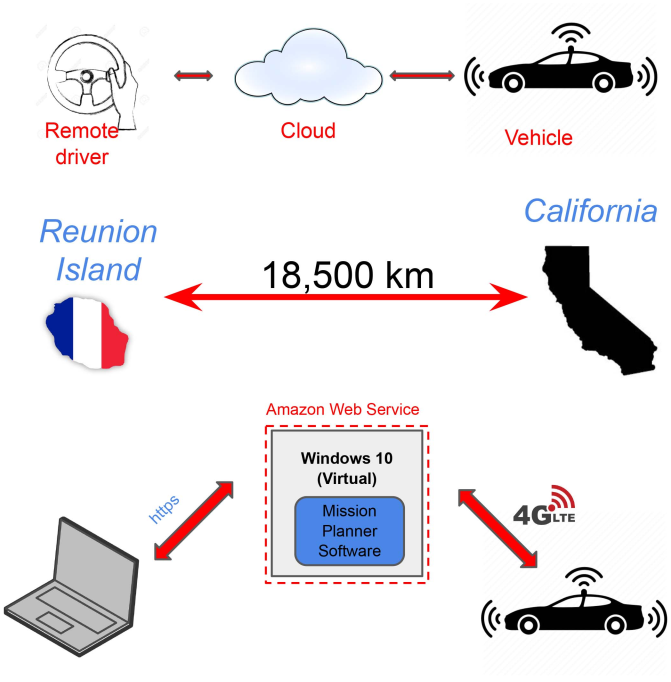


Fig. 2. Cloud-based control station.

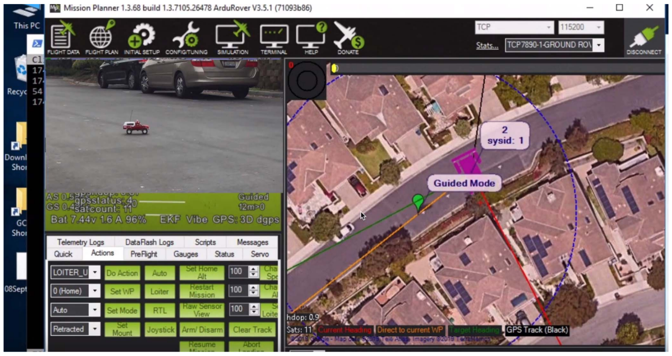


Fig. 3. Mission Planner. This is a screenshot of the laptop on Reunion Island, and shows the Mission Planner software running on the virtual Windows machine in the AWS cloud. The inset (upper left) was recorded locally in California.

2) In Progress: More Sophisticated Cloud-Based Control Station: Although functional, it was not ideal, since the Web browser was a monitor with all of the graphics sent over the Internet. A more streamlined cloud-based control station is under development in the PI's labs [3] and https://github.com/CloudStationTeam.

IV. DEMONSTRATION

A local team in California turned on the vehicle, and the author was physically located 18 500 km away on Reunion Island. The vehicle was carefully monitored to ensure there was no other traffic on the dead-end street where the mission was executed in California. Using a browser interface to the Windows virtual machine (Fig. 3), the author was able to monitor the connection status to the vehicle and (once successfully

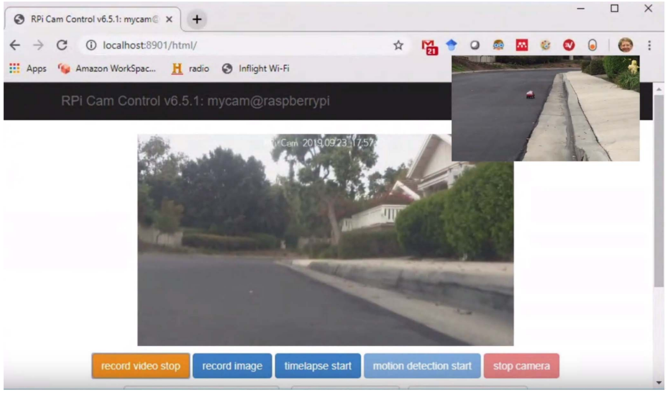


Fig. 4. Web-based video. This is a screenshot of the laptop on Reunion Island, and shows the webcam video viewed in the center of the screen. The inset (upper right) was recorded locally in California.

connected) the vehicle location on a map. Other than turning on the vehicle, and monitoring to make sure there was no other traffic on the street, the team in California did not touch the vehicle for the entire time.

The author then used the Mission Planner software and clicked "drive to here" to instruct the vehicle to proceed autonomously to a waypoint decided on and entered into the system remotely by the author who was located on Reunion Island. The vehicle then proceeded to that waypoint autonomously and stopped. This was executed twice for two different waypoints, whose position was decided randomly and ad hoc by the author at the time of the mission. Although only two waypoints were used, and the vehicle only drove a distance of roughly 30 m, this "small step" represents a giant leap for mankind, demonstrating for the first time around-the-world command and control of a vehicle over the 4G network. Note that no local RC controller was used at all in this instance. The proof of concept could easily be extended to multiple waypoints spaced by arbitrary distances, limited only by the battery life range of the vehicle and the range of the 4G connection, which is virtually unlimited in all but the most remote corners of the Earth.

V. MANUAL REMOTE CONTROL VERSUS AUTONOMOUS ONBOARD INTELLIGENCE

The command and control link was "very" delay tolerant as no real-time manual control is performed, only autonomous commands. The commands are setting waypoints and instructing the rover to drive to a waypoint. As such, the rover has a degree of onboard intelligence to drive using GPS to a waypoint, and there is a degree of user control as well. It is, therefore, the optimum balance of user control and autonomous onboard intelligence for this particular case where the delay is significant.

VI. VIDEO

The vehicle also has an onboard camera. The onboard Raspberry Pi acts as a Web server, and once authenticated, the user can log into the website and get live, real-time video from the vehicle. This is demonstrated in Fig. 4.

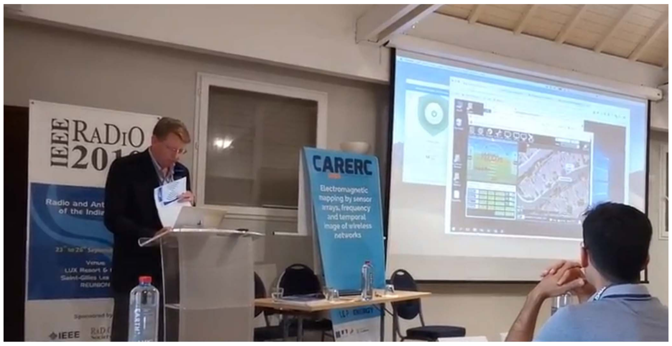
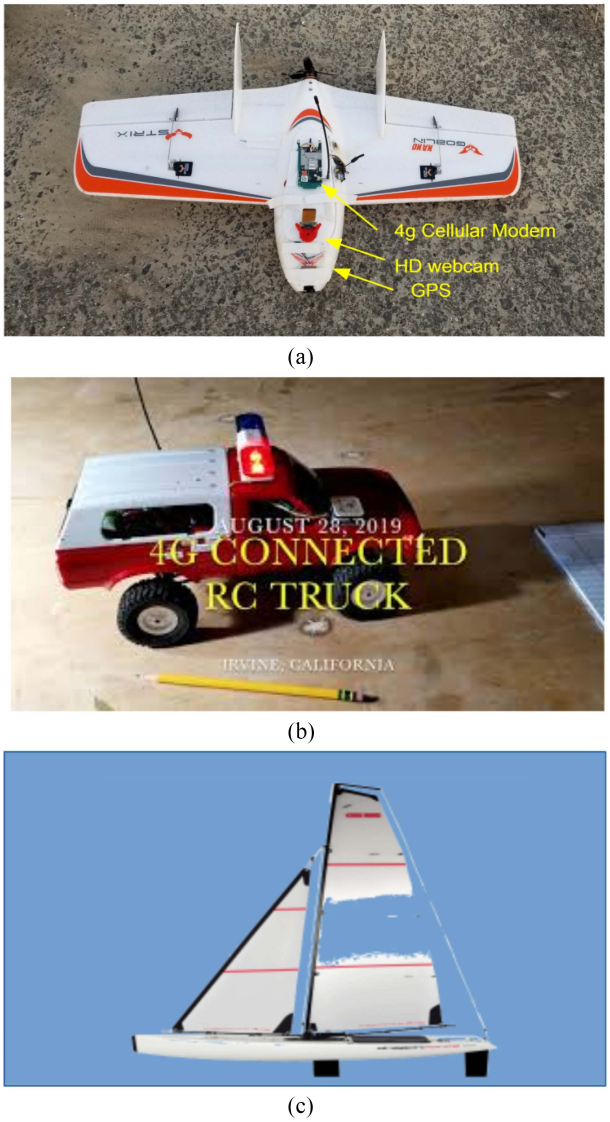


Fig. 5. Live demo by the author at IEEE Radio 2019.



(a)

(b)

(c)

Fig. 6. Air, land, and sea: the technology for vehicular control presented in this article is applicable to all classes of vehicles, illustrated herein. (a) Flying wing (from [2]). (b) Ground vehicle (from [1]). (c) Sailboat.

VII. LIVE DEMO

The demonstration was performed twice, first from a hotel room, to ensure everything was working, and then during the author's talk at the IEEE Radio conference (IEEE Radio and

Antenna Days of the Indian Ocean Conference 2019) (Fig. 5). The audience of the IEEE conference was able to witness real time the command and control of the vehicle in California from the conference location on Reunion Island.

VIII. Discussion

A. Latency

Round trip delay statistics using tracert showed the latency from Reunion Island to the mainland was about 200 ms, with a spread of 100 ms, and an additional 50 ms lag to California from Paris. For this reason, manual piloting of the vehicle was not attempted. This is similar to remote control of the Mars rover by NASA, where the delay is too long for manual control. In addition, the video lag was of order 1 s, so it was only used as an indicator and was not relied on for collision avoidance. How to address this lag and reduce it is a research topic for the future. Note that the speed of light travel time around the world to the antipode is about 60 ms. Therefore, the measured latency should be possible to reduce given enough research and development.

B. Generality: Safe Testbed for Flying Machines (Drones)

The software stack from the Raspberry Pi all the way to the remote user is the same for this and potentially other flying machines (Fig. 6). However, the level of complexity and danger is much lower. Therefore, this can be used as a "testbed" for long range command and control of flying machines without risk. Once the system has been proven, it can easily be translated back into flying machines such as the one we published in 2019 [2].

IX. Conclusion

This work demonstrated the first 4G/LTE control of a vehicle around the world. As such it provides a proof of concept of cellular network-based command and control of vehicles at arbitrary points on the globe.

Appendix
Multimedia

A multimedia demonstration of this work is available at https://youtu.be/1krTjllX_tA. (Make sure to include the underscore after the capital X in the URL, since copy and paste of the URL from pdf sometimes does not include the underscore.)

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From 1998 to 2001, he was a Sherman Fairchild Postdoctoral Scholar in physics with the California Institute of Technology, Pasadena, CA, USA. Since 2001, he has been a Faculty Member with the Department of Electrical Engineering and Computer Science, University of California at Irvine, Irvine, CA, USA. His current research interests include nanoelectronics, probes of cellular and subcellular electrophysiology, radio and antenna propagation and systems (including nano-electromagnetics), and drones.

Dr. Burke has been the recipient of the Office of Naval Research Young Investigator Award, and the Army Research Office Young Investigator Program Award. He has been a Part 107 Licensed Pilot (certificate 390342, issue date 31 August 2016) since the beginning of the FAA drone license program.