Three Low-Cost, Open-Source Sensor Platforms for Structure from Motion Photogrammetry and Mobile Lidar

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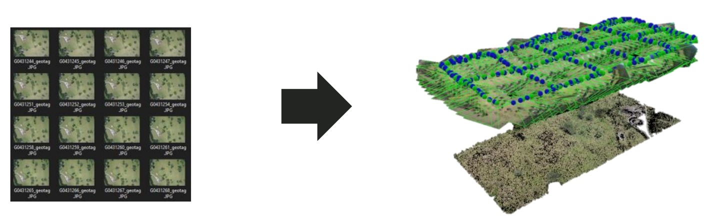
Abstract

While commercial drone platforms such as DJI, eBee, Parrot drones and others have been readily incorporated into scientific research, barriers to use remain in terms of cost and configurability. We present three low-cost, open-source platforms for data acquisition as alternatives. The Hexsoon series of aerial drones provides both entry level (450 mm) and larger scale (650 mm) entry points into the Ardupilot / Cube ecosystem of user-built drones. Similarly, various Autonomous Ground Vehicles (or Rovers) can be built using nearly identical components and the same mission planning software. Finally, pole photogrammetry is presented as an option for when it is not possible to use drones or autonomous vehicles due to environmental or legal restrictions.

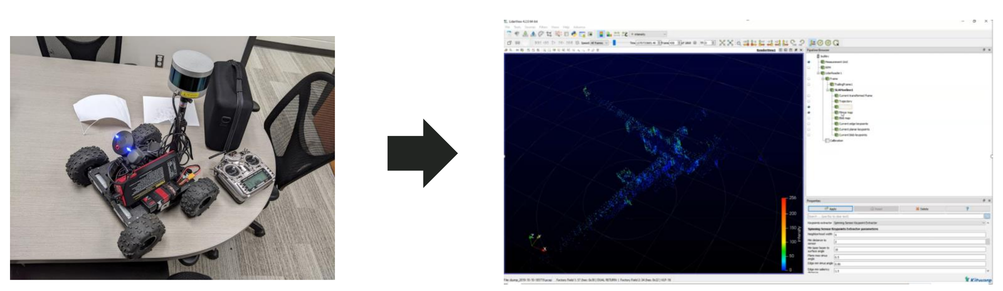
Background

Structure from Motion (SfM) is the process of taking sequential images, usually captured from an aircraft or drone, and using a comparison of keypoints within images to digitally reconstruct the environment in 3D (Westoby *et al.*, 2012; Eltner *et al.*, 2016). Inputs to this process are generally georeferenced images, and outputs are generally point clouds, orthophotos and DEMs/DTMs/DSMs. The technique has its basis in stereo-photogrammetry in which paired photographs were used to measure the environment and create topographic maps. Sometimes multiple cameras are still used, but the motion of the camera essentially replicates the multiple views and so single cameras are often used to simplify the process and/or reduce the weight of the drone. The same technique is applied to thermal imaging and to photographs taken terrestrially.



Structure from Motion uses a sequence of static images to create a 3D model. We use Pix4D in our lab for such projects, although open-source alternatives such as OpenDroneMap exist.

Lidar is a laser scanning technology used to create 3D models of both interior and exterior spaces. The laser scanners themselves can be flown on an aerial platform like an airplane or helicopter (aerial laser scanning or ALS), mounted on a drone (DLS), mounted on tripods for terrestrial use (TLS), or mounted on another mobile system such as a backpack (MLS). We use the term **mobile lidar** to include any small, inexpensive single-user system such as the Velodyne, Livox, or Intel systems intended to capture data from a moving platform. Simultaneous Localization and Mapping (SLAM) algorithms are used to process the raw data, often through use of the Robot Operating System (ROS).



Mobile lidar uses a small laser scanner on a moving platform to collect "frames" of data that are assembled via a SLAM algorithm. LidarView is an open-source software package with SLAM capability.

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Visit ArduPilot.org and CubePilot.org for documentation and discussion forums.

Acknowledgments

We would like to thank Kooper Howerter for his work on building the Rover and Grace Fernandez for pole photogrammetry data collection during Spring 2021. Jack Gonzales also provided much useful insight on SfM and pole photogrammetry. Thanks to Dr. Lynn Resler and Ami Schulte for data collection in Montana.

Pole Photogrammetry

Mounting a camera on a pole is a simple and inexpensive way to collect high resolution and high accuracy terrain data. We have tested a variety of configurations, including long and short poles, different camera angles and orientations, and the impact of using Ground Control Points and RTK GNSS in the workflow.

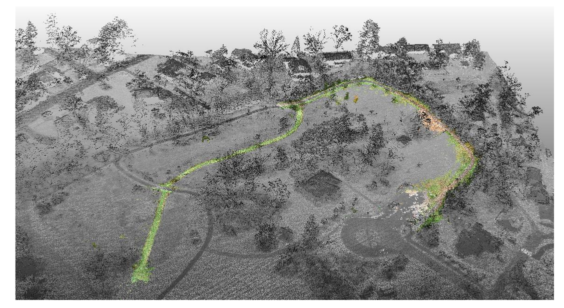
Pole photogrammetry is useful for small site collection, corridor mapping of trails, and operation in areas where conventional drone mapping is either prohibited or impractical. Due to the close proximity of the camera to the surface, sub-centimeter orthophoto and DEM models are supported. Point cloud densities can reach 10 million points per square meter.

The system shown here is composed of a selfie stick with an attachment to fasten on a GoPro Hero9 (20 MP) camera and an Emlid Reach M2 RTK GNSS. Both the angle of the camera and the height of the pole can be adjusted. The system is very lightweight and can be easily held in front of the operator while walking.

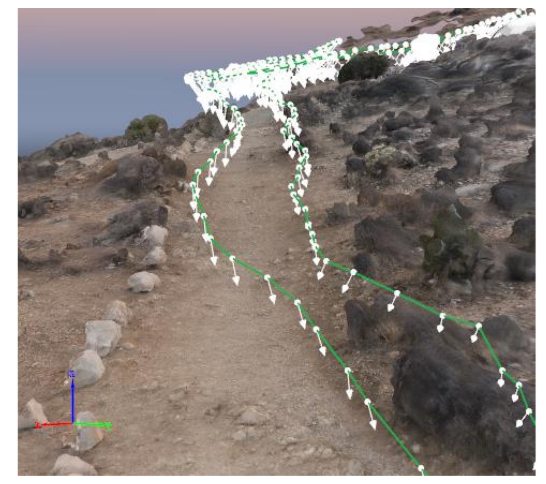
Using the pole mounted system to capture trail data at Joshua Tree National Park.

Video of the Joshua Tree reconstruction is at youtu.be/1v8iGlz4WME or scan the QR code.

3D model reconstruction of Joshua Tree National Park trail data



Trail model from pole photogrammetry (color) overlaid on aerial lidar (gray) at Wong Park in Blacksburg, VA



3D model of Joshua Tree National Park data with camera positions. The camera path is represented by the green line and the camera positions and direction the picture was taken is represented in white. Pictures were taken every 0.5 seconds.

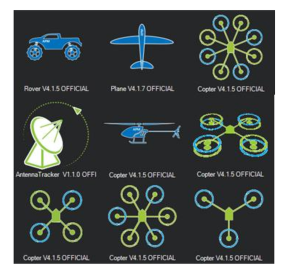
Post-glacial site in Montana imaged with pole photogrammetry. Point cloud density is 10 million points per square meter.

Conclusions

- Longer poles are more suitable for large area capture as they allow for enough image overlap for reconstruction. Shorter poles work well for corridor mapping applications and small site capture.
- More than drone-based SfM, pole photogrammetry is particularly prone to "ghosting" in which the same area is reconstructed multiple times at slightly different orientations and elevations. However, the use of both RTK GNSS and Ground Control Points greatly facilitates accurate reconstruction.
- Scenes with uniform textures, repeating patterns, or slight movement (such as autumn leaves on the ground or plants moving in the wind) do not reconstruct as well. Literature suggests that increasing the distance from camera to target (e.g., with a longer pole) may help. Intense shadows and dark lighting lead to poor reconstruction – reconstruction is only as good as the pictures.
- While software such as Pix4D can calibrate cameras during the reconstruction process, a pre-calibration noticeably improves results with pole photogrammetry.

The Cube / ArduPilot Ecosystem

All of the unmanned vehicles we use are built on the ArduPilot and CubePilot family of hardware and software. ArduPilot is an open-source project that provides autopiloting functionality for a wide range of vehicle types, including large and small drones, copters, rovers, planes and more. The ArduPilot system is used by a number of hardware manufacturers, including CubePilot, who manufacture the Cube autopilot. An autopilot is the centerpiece of a vehicle, like a CPU for a computer. A Cube autopilot running on ArduPilot firmware is the core of each vehicle we use. Then, we add modules from the supported ecosystem to suit the specific purpose of each vehicle. Common peripherals that we employ include high-precision telemetry radios, obstacle avoidance, high-precision RTK GNSS and an unlimited number of sensors including multispectral cameras and lidar modules.



The ArduPilot system supports many different vehicle types.

RTK GNSS

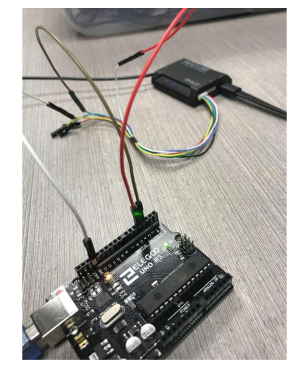
Real-Time Kinematic (RTK) positioning uses a two GNSS receivers to achieve centimeter-level accuracy. A stationary *base* unit provides corrections to a *rover* unit via WiFi, Bluetooth, LoRa radio locally, or through the Internet by means of an NTRIP server. We use the Emlid Reach M2 unit on many of our builds, a small lightweight multiband receiver suitable for mounting on mobile platforms. The CubePilot Here3 integrated GPS and compass (used on our Hexsoon drone) also supports RTK correction. Within the Blacksburg area, we publish corrections via a continuously operating, publicly accessible NTRIP server at:

rtk2go.com:2101/SNIP::MOUNTPT?NAME=neilreach

An Emlid Reach M2 RTK GNSS unit paired with a GoPro Hero9.

RTK & Arduino Integration

Combining an Arduino Uno with an Emlid Reach M2 Multi-band RTK GNSS module proved to be an efficient way to geolocate non-standard sensor streams such as temperature and humidity data. The M2 can output an NMEA sentence stream, a comma separated value string that contains position and fix quality information. The Arduino Uno acts as a data logger that processes the incoming position data using public libraries such as TinyGPS, Sodaq_DS3231 (DS3231 Clock and Temperature sensor), and DHTNEW (AM2303 Temperature-Humidity sensor). The Arduino SD library allows for data to be written in real-time to an SD card.



Arduino Uno integrated with an Emlid Reach M2 RTK GPS.

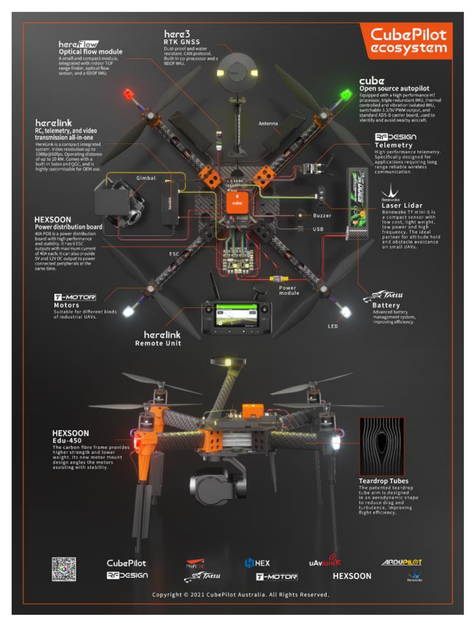
Hexsoon Drone

The Hexsoon EDU450 is a low cost 450 mm drone airframe specifically designed with the Cube autopilot in mind. Built with carbon fiber material and tear drop shaped arms, the aerodynamic structure is lightweight and strong.

The Hexsoon is a reference frame used to help beginners learn to assemble drones from pre-selected parts, and to provide a basis to test new design innovations. The kit ($250) contains nearly all parts needed for assembly (carbon fiber plates and arms, motors, ESCs, propellers, and power distribution board). The builder must separately purchase the flight controller (e.g., the Cube and GPS kit for $400), RC transmitter and telemetry kit, and batteries.

The flight controller is the brain, controlling and monitoring each component of the drone. The transmitter and receiver allow for remote control access, relaying commands from the user to the flight controller which in turn distributes the commands to the other components on the frame. Once all of these components are working properly a single lipo battery connection is needed to power the drone and it is then ready for flying.

The Hexsoon and other custom-built drones allow for complete end-user configurability. Any combination of sensors can be added, making this an ideal platform for scientific research. The ease of assembly and repairability makes it well-suited for education. NEIL expects to use the Hexsoon in combination with a FLIR thermal camera to collect imagery during Summer 2022.



The CubePilot ecosystem, shown with a Hexsoon 450 build.
(Image from cubepilot.org)

NEIL lab members Cameron Neal and Andrea Granger assemble the Hexsoon EDU450.

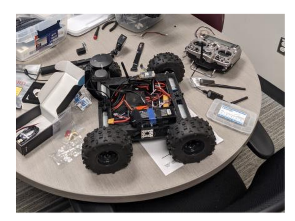
Rover

Rovers, or autonomous ground vehicles, are being increasingly utilized as alternatives to airborne drones for the purposes of mapping, imagery, and data gathering. Rovers are limited to ground level, which presents unique challenges in navigating terrain, but they have several advantages over their airborne counterparts. Notably, rovers are less limited by legal regulations, weight restrictions, complexity, and can operate in tricky environments such as beneath tree canopies and inside buildings. Many rovers are currently being used for precision agriculture.

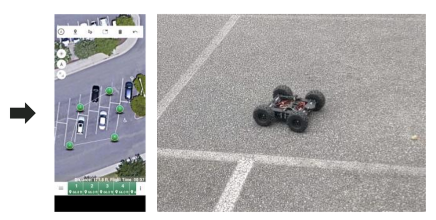
Our focus is on this ability of a rover to map indoor spaces and provide coverage in areas a traditional drone may miss. Our basic rover build was constructed using 3D printed components, and the open-source ArduPilot ecosystem. We have used both gimbal-mounted cameras and lidar sensors on the Rover, and expect to test a FLIR thermal camera during the Summer 2022.

Future planned upgrades include a long-range radio transmitter and video relay system (HereLink, with 20 km range). Unlike aerial drones, rovers have no limitation for Beyond Visual Line of Sight operations, so long-range operation could greatly facilitate corridor mapping. Much larger autonomous ground vehicles can be constructed on the same platform, needing only larger motors, motor drivers, and batteries, but keeping the same electronics. We expect to build such a system to tow heavy sensors like ground penetrating radar for collaborative archaeological projects.

Rover POV during a test at Wong Park.

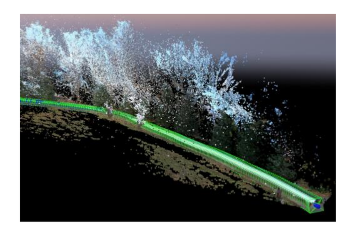


Construction



Planning simple missions with an Android app.

Reconstruction of pavement using Pix4D.



Reconstruction in Pix4D.