Imaging of Earthquake Faults using Small UAVs as a Pathfinder for Air and Space Observations

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Abstract— **Large earthquakes cause billions of dollars in damage and extensive loss of life and property. Geodetic and topographic imaging provide measurements of transient and long-term crustal deformation needed to monitor fault zones and understand earthquakes. Earthquake-induced strain and rupture characteristics are expressed in topographic features imprinted on the landscapes of fault zones. Small UAVs provide an efficient and flexible means to collect multi-angle imagery to reconstruct fine scale fault zone topography and provide surrogate data to determine requirements for and to simulate future platforms for air- and space-based multi-angle imaging.**

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1. INTRODUCTION

Plate tectonics drives motions of the Earth's crust. In California, the Pacific Plate moves northwest relative to the North American Plate at a rate of about 52 mm/yr [1]. The boundary is over 300 km wide. The San Andreas fault takes up about 23 mm/yr of the motion in southern California [2] and about 34 mm/yr in Central California [3]. For the last three decades, surface motions have been measured using Global Positioning System (GPS) measurements. The plate boundary rate and distribution in California is measured using a network of continuous GPS stations, spaced on average about 10-20 km apart. Velocities are accurate to about 1 mm/yr. The network allows an assessment of which faults are active, how fast strain is accumulating in the short term, and how deep they are locked.

GPS measurements capture behavior of the crust as it accumulates tectonic strain over the long-term, moves abruptly from earthquakes, and readjusts following earthquakes from afterslip on ruptured faults and relaxation of the Earth's crust. Time-dependent measurements are necessary for understanding the elastic and viscous properties of the crust, but information about details of fault characteristics can be missed due to sparse station coverage around the faults.

Interferometric Synthetic Aperture Radar (InSAR) provides detailed images of surface motions and change associated with earthquake processes, complementing GPS measurements. Several international missions supply InSAR science data and the US and India will launch the NISAR mission in late 2021, which will provide radar imagery at an 8 day repeat interval. In California, an airborne InSAR instrument called UAVSAR is flown every 6-12 months to provide crustal deformation measurement ranging from southern California to north of Napa. UAVSAR has a spatial resolution of 7 m for 90x15 km swaths. Local measurements are accurate to about 1 cm and relative displacements at scales of km are accurate to a few cm. The instrument has imaged three earthquakes and aseismic slip on many faults, particularly in southern California [4-7].

Answers to several questions will reduce uncertainty in assessment of earthquake hazard at the Pacific – North American plate boundary and for other parts of the world. In this paper, we focus on California (Figure 1).

1) *How are plate boundary motions distributed onto faults?*

Measurements of crustal deformation and geological observations spanning the plate boundary can characterize the partitioning of slip between faults. Understanding the history of earthquakes on a fault can characterize the average recurrence interval and the loading rate derived from GPS geodesy can be

Figure 1. California Pacific-North American plate boundary fault system. Faults are marked by black lines. Recent earthquakes are noted in red. State boundaries are marked in red. Target sites for small UAV observations are marked by blue boxes.

compared with slip per event and/or slip rates from geology to characterize slip deficit and associated hazard on individual faults within the greater plate boundary.

2) *How do faults within the plate boundary interact?*

Simulations of plate boundaries that include tectonic loading rates and frictional properties of faults provide long, albeit simulated, catalogs of fault ruptures [8]. These simulated ruptures can be explored for statistically significant repeatable fault rupture sequences and emergent behavior of ruptures in the fault network simulation. GPS station position time series can be explored for transient motion that may indicate transfer of strain from one fault to another through the viscoelastic crust. This type of transient motion has not been observed in GPS data, but should be explored as time series become longer and improvements in processing and analysis reduce error. UAVSAR, spaceborne InSAR (hereafter referred to as InSAR), and ground-based geological mapping all confirm that earthquakes can trigger shallow slip on faults more than one fault dimension from the main rupture. Recent GPS and UAVSAR measurements suggest that large earthquakes can cause delayed triggered slip on large faults [9]. High resolution topographic datasets are poised to yield insight to fault interaction on longer timescales, and as such may be as valuable as advanced SAR and GPS measurements.

3) *What fraction of the total plate boundary slip occurs aseismically?*

Earthquake fault zones contain a core of highly damaged rocks that can be tens of meters across surrounded by a 2-3 km wide damage zone [10]. There can be a single fault strand

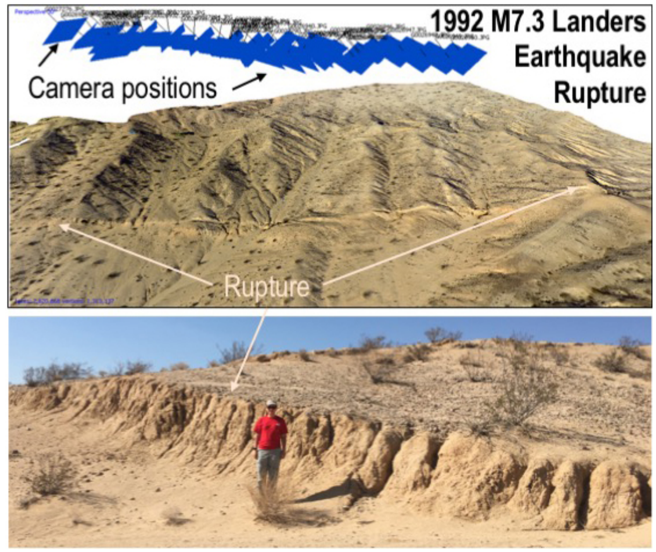

Figure 2. Figure 2. 1992 M7.3 Landers earthquake rupture. Topographic image was created from multiangle imaging collected from a small UAV flying at 90 m altitude above ground. Data were collected in June 2016, nearly a quarter century after the earthquake occurred. Top panel shows camera images and reconstructed topography with 4 cm resolution. Bottom panel shows ground based image for scale.

or several strands within the fault zone. Throughout the crust and plate boundary strain accumulation may be relieved aseismically, but it likely that the majority of plate boundary aseismic slip occurs within fault zones. Determining the occurrence and amount of aseismic slip requires study of surface deformation at high resolution in space and time. It also can provide information related to the mechanical properties of the fault zone materials, especially in combination with observations of geologic and geomorphic features, s, and high-resolution seismic surveys.

4) *In which direction will earthquake ruptures on faults propagate?*

The compositional and mechanical properties of fault zones are often variable across the zone and often asymmetric across faults. Part of the variability can be due to fault blocks of different materials slipping past each other. Repeated earthquakes cause damage to the crustal rocks surrounding the faults, which over the long-term creates the fault zone. Earthquakes tend to rupture in the direction of the more compliant side of a fault zone [11]. What causes a side of a fault to be more compliant can be geologically controlled and/or due to rock damage from repeated earthquake ruptures propagating in a consistent direction. The direction of rupture through and along geologic structures, basins, and mountains can amplify or reduce the amount of shaking that occurs. Thus, rupture directivity can have a large impact on earthquake damage and losses that occur from an event. For example, a rupture along the southern San Andreas fault that originates in the south would produce more intense shaking

Figure 3. Observation area for the locked Anza section of the San Jacinto fault at Table Mountain (Bud's Ranch), which is capable of producing a M7.3 earthquake. Upper right shows location in California and local survey area. Left panel shows processed color digital elevation model using nadir pointing images only. Lower right panel shows raw off-nadir image, which when added to the solution will fill in the holes on the sides of the trucks and steep slopes.

in Los Angeles compared to a rupture propagating from north to south [12].

What measurements can inform us about plate boundary processes?

Across key parts of the California plate boundary, surface deformation measurements are well covered with GPS and UAVSAR. While it would be beneficial to collect UAVSAR images more frequently, the resolution of UAVSAR and GPS measurements are sufficient for measuring crustal deformation across fault zones and across the plate boundary. However, measurement of details within the fault zones themselves are largely non-existent except for a handful of locations. High resolution seismic reflection study, high resolution topography and geological studies are needed to fill in these missing details of fault zones and their behavior. In this paper we show that small UAVs can be used to deliver imagery and topography of fault zones to provide key missing science measurements and serve as a demonstration and pathfinder for air and spaceborne topographic imaging instruments.

2. TOPOGRAPHIC IMAGING

Fixed-point multi-angle staring imaging produces color draped topographic images of landscapes, components of which are records of the permanent deformation from accumulated earthquakes (Figure 2). Structure from motion (SfM) methods recover 3D color imagery. These imaging data can be used for science study and also to produce imagery at various resolutions in order to assess measurement requirements for characterizing fault zone processes. Air or spaceborne measurements would likely have a larger ground sample distance, but also a larger field of view than small UAV measurements. The Landers earthquake rupture example illustrates that sub-meter imagery is required to capture details of surface rupture and erosional features (Figure 2).

We have been using small UAVs to collect imagery over fault zones in areas up to 0.4 x 0.7 km, enough to span multiple strands of the San Andreas and San Jacinto faults as well as the 1992 M7.3 Landers earthquake rupture. We have experimented with nadir and off-nadir imagery. We typically fly at 90 m using a 1954x1473 pixel lens with a 70x55m field of view at nadir. The nadir imagery provides excellent digital surface models for shallow slopes, but misses details in areas with steep slopes (Figure 3). The off-nadir imagery fills in details of the steeply sloping areas.

We have collected hundreds of images across fault zones, collected as both nadir and off-nadir imagery. For ground control points, we use round colored targets that are 66 cm in diameter. We typically place about one dozen ground control points around the survey area and survey them using differential GPS. These ground control points are located in the imagery to produce precise georeferenced solutions. We process the data using internal JPL software, Agisoft Photoscan, and Pix4D. We calibrate the camera lens at JPL for processing the data. The horizontal resolution of the topographic data products that we have produce is 3-4 cm.

We have observed many features in the imagery relevant to studies of plate boundary process. These include fault traces,

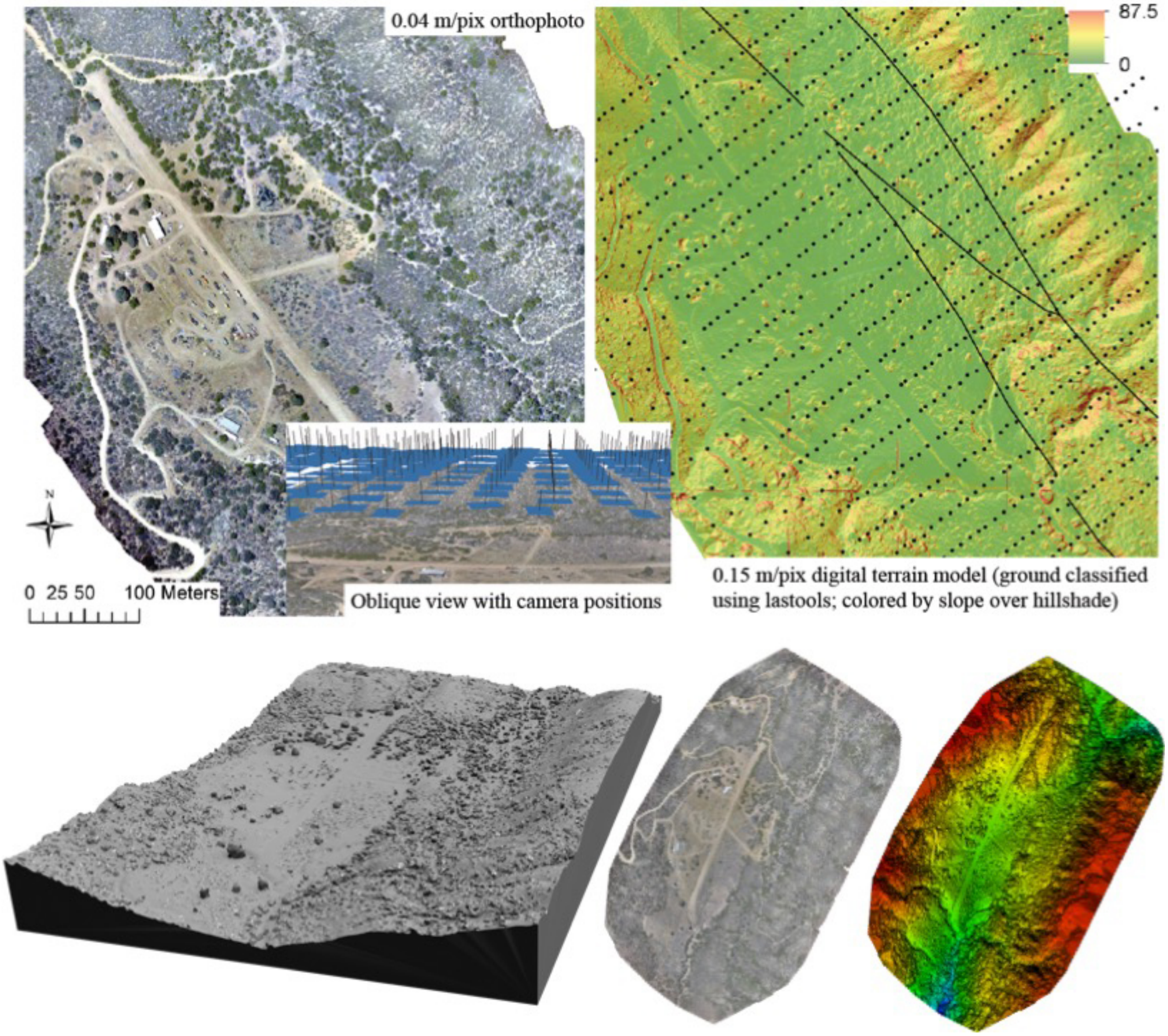

Figure 4. San Jacinto Fault imagery, topography, seismic stations, and faults. Orthophotos have 4 cm per pixel resolution. The topography at top right is ground points interpolated to 15 cm per pixel color coded by slope. Dots show seismic array deployed by Ben Zion and Vernon. We are evaluating the fault geometry currently mapped as the black traces. Lower left shows 3D model in oblique view of the fault. Black dots in lower left of the mesh are tress. Scale is 0.45 x 0.75 km and captures the width of the fault zone. Lower center image shows color reconstructed topography from nadir view, roughly aligned with the topography. Lower right shows digital surface model, shaded by elevation.

lineaments, fault scarps, offset drainages, offset cultural features, and many other classic tectonic landforms. We will carry out additional analysis to compute geomorphic metrics at the sites such as scarp height and morphology, stream offset distances and the geometry of fault traces, as examples. We will use the scales of these features to determine the threshold resolution required for more remote measurements from higher altitudes. We have collected data at several sites including the San Jacinto fault, the faults ruptured in the 1992 Landers earthquake, the Southern San Andreas fault in the Mecca Hills, the creeping San Andreas fault in central California and an iconic cinder cone in Owen Valley, CA.

At the San Jacinto site, we observed lineaments along small topographic benches that match fault strands identified in the subsurface velocity structure obtained using a dense array of seismometers (Qin et al, 2016). Red colors were observed within the fault zone that may indicate alteration of iron species due to fluids moving more freely within the damaged rock of the fault zone compared to the neighboring rock (Figure 4).

These observations, though somewhat disparate, begin to illustrate the potential of optical imagery to achieve scientific objectives outlined in this paper. Characterization of the topography of fault zones as well as patterns of deformation

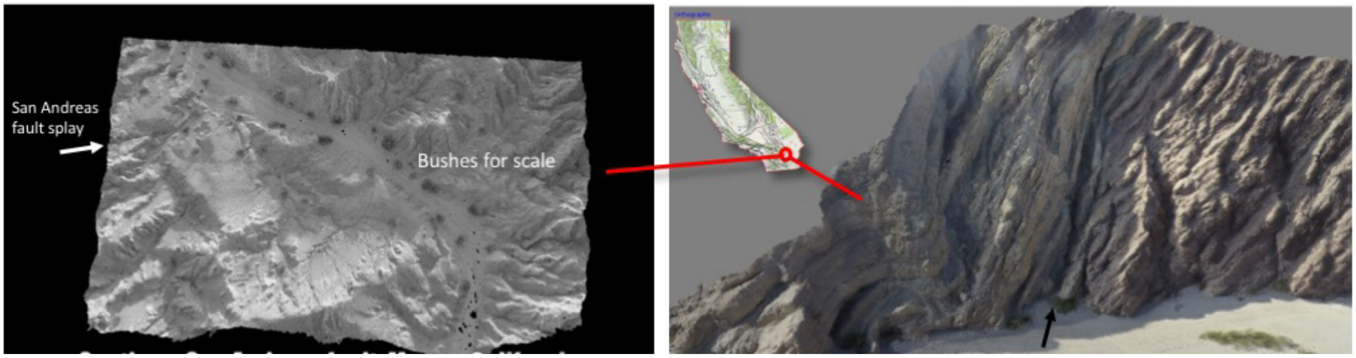

Figure 5. Complex deformation along the San Andreas Fault zone in the Mecca Hills, CA. Left panel shows strand on east side of main fault. Right panel shows well developed strand of the fault and folded rock just west of the fault strand.

within and between fault zones can be achieved by repeated, high resolution topographic and optical surveys. These can serve as a complement to other established and developing measurement methods including GPS, UAVSAR and InSAR.

Along the the 1992 Landers earthquake rupture, a fault scarp that is still well preserved nearly a quarter of a century after the earthquake is clearly visible and can be characterized quantitatively (Figure 1). Stream channels are far more intricate and well developed on the uplifted east side of the rupture due to a steepening of slope on that side of the fault from the earthquake. We also identified fault branches and jogs in the observations.

The southern San Andreas fault observations show several parallel strands of the San Andreas fault (Figure 5). The width of the zone is about 4 km. The strands consist of pulverized clay and typically are on the order of 1–2 m wide. The pulverized clay erodes more easily, resulting in topographic depressions. Observations of the creeping section of the San Andreas fault show numerous offset stream channels and sag ponds from extensional pull apart sections between strands of the fault. We also observed fences that have been offset where they cross the fault and gullies that have formed along the fault. We collected initial data of road cracks, which can be re-observed over time with the goal of measuring the local fault creep.

We collected data over the Fish Springs cinder cone in the Owens Valley just north of Lone Pine. The Owens Valley fault is mapped to the west, north, and south of the cinder cone [13]. A splay of the fault lies west of the cinder cone, but the fault forks into two splays just north of the cinder cone. While the fault is not mapped as extending into the east side of the cinder cone, the results suggest that the fault does continue through the east side of the cinder cone. A linear erosional pattern that has caused slumping on the east side of the cinder cone is located along the southward extension of the mapped section of the fault. Further analysis of the data will elucidate whether the fault does extend into the cinder cone.

Our data collection using a small UAV helps us prepare for designing future data collection platforms. We are experimenting with a concept to simultaneously collect topography and InSAR observations on NASA's UAVSAR platform. UAVSAR views the ground from a side-looking oblique look-angle. The topographic resolution degrades greatly for reconstructions from oblique images. Therefore, any concurrent topographic measurements should be observed close in time to be roughly concurrent with the radar images either closely in time on the same platform or a separate platform.

3. Conclusions

Small UAVs allow for collection of high resolution topography from optical images. This prepares us to design methods for much wider data collection. High resolution topographic measurements on a global scale would advance the understanding of earthquake and other terrestrial land surface processes. We are using the results for science analysis, to develop design concepts for air and spaceborne instruments, and to develop the workflow and software system necessary to carry out the science and analyze the large data volumes. California provides ideal locations for proof-of-concept because it is easily accessible with small UAVs, has a wide range of faulting types, and is exceptionally well instrumented, allowing for calibrating and validating results.

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REFERENCES

[1] DeMets, C., Dixon, T.H., 1999. New kinematic models for Pacific-North America motion from 3 Ma to present, I: Evidence for steady motion and biases in the NUVEL-1A Model. Geophysical Research Letters, 26(13), pp.1921-1924. [2] U.S. Munitions List, sections 38 and 47(7) of the Arms Export Control Act (22 U.S.C. 2778 and 2794(7).

[2] Keller, E.A., Bonkowski, M.S., Korsch, R.J., Shlemon, R.J., 1982. Tectonic geomorphology of the San Andreas fault zone in the southern Indio Hills, Coachella Valley, California. Geological Society of America Bulletin, 93(1), pp.46-56.

[3] Moore, D.E. and Rymer, M.J., 2007. Talc-bearing serpentinite and the creeping section of the San Andreas fault. Nature, 448(7155), pp.795-797.

[4] DeLong, S.B., A. Donnellan, D.J. Ponti, R.S. Rubin, G. Seitz, D.P. Schwartz, C.S. Prentice, T.E. Dawson, J.J. Lienkaemper, K.W. Hudnut, C. Rosa, A. Pickering, J.W. Parker, in press, Tearing the terroir: Details and implications of surface rupture and deformation from the 24 August 2014 M6.0 South Napa earthquake, California, Earth and Space Science.

[5] Donnellan, A., L. Grant Ludwig, J.W. Parker, J.B. Rundle, J. Wang, M. Pierce, G. Blewitt, S. Hensley, 2015, Potential for a large earthquake near Los Angeles inferred from the 2014 La Habra earthquake, Earth and Space Sci, 2, 378–385, DOI: 10.1002/2015EA000113.

[6] Wei, S., J-P. Avouac, K.W. Hudnut, A. Donnellan, J.W. Parker, R.W. Graves, E. Fielding, Z. Liu, F. Cappa, and M. Eneva, 2015, The 2012 Brawley Swarm Triggered by Injection-Induced Aseismic Slip, Earth and Planetary Science Letters, 422, 115-125.

[7] Donnellan, A., J. Parker, S. Hensley, M. Pierce, J. Wang, J. Rundle, 2014, UAVSAR Observations of Triggered Slip on the Imperial, Superstition Hills, and East Elmore Ranch Faults Associated with the 2010 M 7.2 El Mayor - Cucapah Earthquake, Geochemistry, Geophysics, Geosystems, 15, doi: 10.1002/2013GC005120.

[8] Sachs, M.K., Heien, E.M., Turcotte, D.L., Yikilmaz, M.B., Rundle, J.B. and Kellogg, L.H., 2012. Virtual California earthquake simulator. Seismological Research Letters, 83(6), pp.973-978.

[9] Vincent, P., 2000. Aseismic slip events along the southern San Andreas fault system captured by radar interferometry. In Proceedings of the 3rd Conference on Tectonic Problems of the San Andreas Faul System, G. Bokelmann, RL Kovach (editors) (p. 193).

[10] Ben-Zion, Y. and C. G. Sammis, 2003. Characterization of Fault Zones, Pure Appl. Geophys., 160, 677-715.

[11] Ben-Zion, Y., Shi, Z., 2005. Dynamic rupture on a material interface with spontaneous generation of plastic strain in the bulk. Earth Planet. Sci. Letters, 236, 486– 496.

[12] Olsen, K.B., Day, S.M., Minster, J.B., Cui, Y., Chourasia, A., Faerman, M., Moore, R., Maechling, P., Jordan, T., 2006. Strong shaking in Los Angeles expected from southern San Andreas earthquake. Geophys. Res. Lett., 33, L07305, doi:10.1029/2005GL025472.

BIOGRAPHIES

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Joseph Aletky *is an expert in Unmanned Aerial Systems with over 20 years of experience, Instructor Qualifications, and certifications on multiple large UAS platforms. He is an FAA rated UAS Operator, Commercial Helicopter Pilot, and Private Fixed Wing Pilot. He has accumulated thousands of hours operating unmanned aircraft, including combat 3 tours overseas flying UASISR missions in support of US and Allied forces. In 2011 he received an award from the Department of Defense for his critical role supporting our troops during Operation Enduring Freedom. Using advanced rendering software, he uses aerial imagery from various sensors including electro optical, infrared, multispectral, and Lidar and to construct 3D georeferenced orthomosaics and digital elevation models for science and survey data. In addition, he also designs and builds custom SUAS, creating some of the best selling products for large civil UAS companies. He has recently founded his own company- SUAVX, providing services utilizing his skill sets with roles such as UAS Consultant, UAS Instructor, and UAS Integrations Specialist, while designing and manufacturing custom VTOL UAS for clients and science missions.*

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