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Integrated Data Capture, Processing, and Dissemination in the al-Ula Valley, Saudi Arabia

UAV aerial photograph of the excavations and stone basin at Khuraybah (ancient Dedan), al-Ula, Saudi Arabia. Photograph courtesy of L. Passone.

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In late 2013, a joint archaeological and computer vision project was initiated to digitally capture the archaeological remains in the al-Ula valley, Saudi Arabia. The goal of our team of archeologists and computer scientists is to integrate 3D scanning technologies to produce 3D reconstructions of archaeological sites. Unmanned Aerial Vehicles (UAVs) serve as the vehicle which makes this scanning possible. UAVs allow the acquisition of 3D data as easily from the air as from the ground. This project focuses on the recent excavations carried out in ancient Dedan by King Saud University and the country's conservation of the Lihyanite "lion tombs" carved into the ancient city's cliff faces. Over the next several years this site will be used as a test bed to validate the potential of this emerging technology for rapid cultural heritage documentation. We additionally scanned several areas in Mada'in Saleh, an ancient Nabatean city filled with monumental carved sandstone tomb facades, rivaled only by the capital of the Nabatean empire: Petra.

Under the King Saud University's Dedan (al-Ula) Archaeological Excavation Project (al-Said 2009) and the Saudi Commission for Tourism and Antiquities (SCTA), an initial digital scan using low altitude flying UAVs was conducted at Dedan (Khuraybah) and Mada'in Saleh. In this article, we present our initial results and methodology including the use of UAVs and modern advances in remote sensing computational techniques.

Dedan – A City on the Crossroads of Ancient Arabia and Modern Technology

Once an integral part of the North-South trade artery of the Arabian Peninsula, ancient Dedan was one of the most impressive and extensive eighth century B.C.E.–first century C.E. trade centers in Saudi Arabia (fig. 1). Nestled between the rugged red sandstone mountains and lush date palm farms, the ruins of Dedan and their excavation make an ideal open air museum for tourists that have the rare privilege to visit the archaeological site. The ruins of Dedan (known locally as Al-Khuraybah) is located 4 km north of the modern city al-Ula (26.6549°, 37.9131°, WGS1984). Dedan is strategically located in the al-Ula oasis adjacent to Wadi al-Qara where abundant water resources could be harvested for agriculture. The ruins stretch for ca. 2 km around the eastern face of a sandstone mountain range called Jabal Dedan. The central rectangular palace at its northern end as well as the "lion tombs" (of the Lihyanite kingdom, fifth century B.C.E.) carved into the cliff face at the southern end are visible from satellite imagery.

The settlement of al-Khuraybah (Dedan) is the ancient capital of the Dedanite kingdom (eighth–sixth centuries B.C.E.) and later

the primary trading center of the Lihyanite kingdom (sixth–first centuries B.C.E.) until its collapse and abandonment in the first century B.C.E. partially accelerated by a documented earthquake in the region (al-Said 2010). It was at this time that the Nabateans took control of the area and focused the lucrative incense trade through Hegra (Mada'in Saleh) located 30 km north of Dedan. Over the past eight seasons of excavation an extensive area of Dedan's ruins were exposed. Excavation and conservation has been conducted by King Saud University with principal investigators Dr. Said al-Said and Dr. Abdulaziz Saud al-Ghazzi. Although conservation techniques have been employed to protect the site, the majority of the walls constructed used mud-brick and with the harsh weather conditions in al-Ula, it is inevitable that the structures will eventually decay and change in appearance. Considering these factors, the digital documentation of Dedan poses a solution both for documentation and virtual site observation by both archaeologists and tourists.

Unmanned Aerial Vehicles (UAVs) and Archaeology

A key component of our project is the development of a streamlined scanning system using UAVs for archaeology. A UAV is an aerial vehicle (plane, helicopter, blimp) that does not have a human pilot on board but is controlled remotely. Some UAVs are capable of autonomously following a pre-programmed flight path maintaining altitude and speed delivering images with the correct overlap for 3D reconstruction. Until recently, UAVs consisted primarily of different types of planes or helicopters that required extensive operational experience. For our low altitude scanning we used a new type of UAV called a multirotor copter. A multirotor copter uses between three to eight motor controlled counter-rotating propellers to balance itself and to be able to move in all degrees of freedom. A multirotor with four propellers is called a quad-copter and by extension an octo-copter would employ eight propellers and motors. A multirotor requires less flight training and with added GPS and a barometric (altitude) sensor they hold their position even in strong winds. Similar to helicopters, a quad-copter can take off and land within a small area with the ability to rotate and move in all directions. The amount and size of propellers provides a tradeoff between payloads (e.g. size of camera that can be mounted) and different flight times to be achieved. These features make a multirotor UAV a highly configurable platform for aerial capture of complex archaeological sites requiring multiple angles.

Figure 1. Map of northern Saudi Arabia, with research areas and sites highlighted. Courtesy of N. Smith; ©Google Earth.

The application of UAVs to archaeology is an emerging technology. Lambers et al. (2007) and Guidi et al. (2008) were some of the first to use airborne photogrammetry in archaeological research to generate highly detailed 3D reconstructions, orthophotos, and digital elevation models. This was followed by a number of projects that directly sought to employ UAVs for aerial photogrammetric capture (Barazzetti et al. 2010; Irschara et al. 2010; EisenBeiss and Sauerbier 2010; Levy et al. 2010; Remondino et al. 2011). Our own work, (Levy et al. 2010; Levy et al. 2012) has undergone a rapid evolution as new technology emerged and we adopted it into our field recording methods. In 2000, we started with boom systems and the first commercially available digital cameras, followed in 2006 with our first aerial balloon, and most recently with UAVs.

Aerial scanning's contribution to the archaeological field is its ability to achieve perspectives of architecture not possible from ground scanning. Many cultural heritage sites and especially archaeological excavations contain a high level of occlusion. Occlusion is detrimental to scanning because anything that is concealed by another object is not scanned. It results in large gaps or holes in the data that can only be resolved by conducting more scans from different locations. Archaeological sites are very complicated to scan because they often consist of walls and structures that occlude the majority of the site. Even with multiple scans it is not always possible to scan particular areas and achieve comprehensive capture. However, whether it is ledges blocking the upper portions of a carving or a complex system of small rooms within an excavated site, these areas are easily viewed from the air (see figs. 2–3). A large area can be captured in minimal time using aerial scanning with limited occlusion. Additionally, aerial scanning allows the capture of sites from the same perspective needed for publication: as top-down architectural drawings. They provide a comprehensive layout of a site revealing how architecture and terrain are interconnected.

The Technology Behind the UAV

Over the past year, our team has been developing the hardware and software required to conduct automated aerial 3D scanning. The UAV provides the means to capture images from the air but it is the software used to convert these 2D images into 3D models and merge them with ground scans that makes the technology revolutionary.
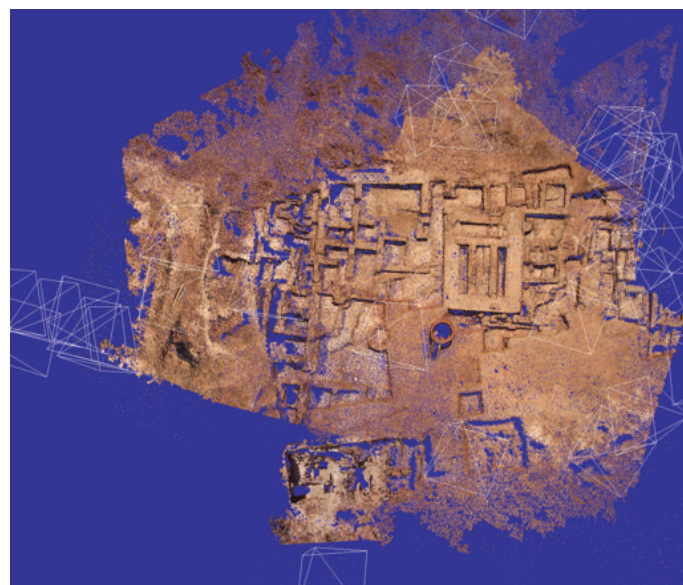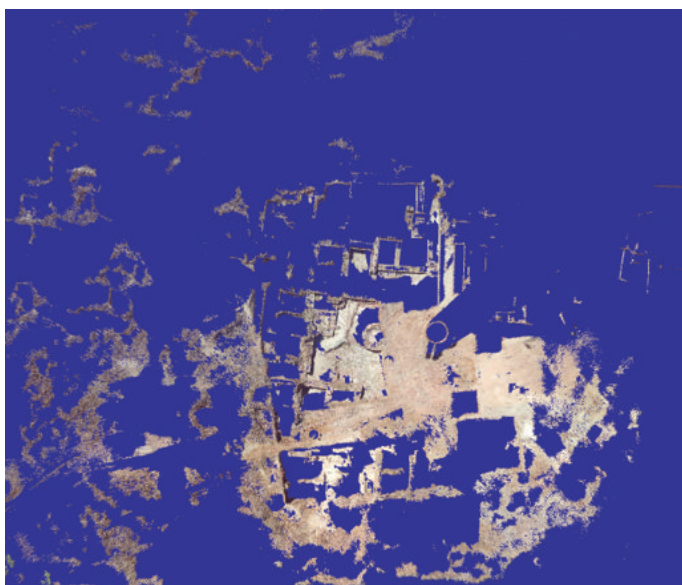
Figure 2 (above). Comparison between laser scans of Dedan from a top-down perspective (left) and the same area captured from the air (right). Note camera positions of UAV represented here as white wireframe pyramids.

Figure 3 (below). Comparison between a laser scan of Qasr Al-Farid (Mada'in Saleh) (left) and the same area captured from the ground and air using SfM (right). Note on the left how the laser scan's ledges have occluded portions of the façade in blue. The white wireframe pyramids in the left SfM scan represent the different areas images were taken: both terrestrial and airborne SfM were automatically combined together. Courtesy of N. Smith.
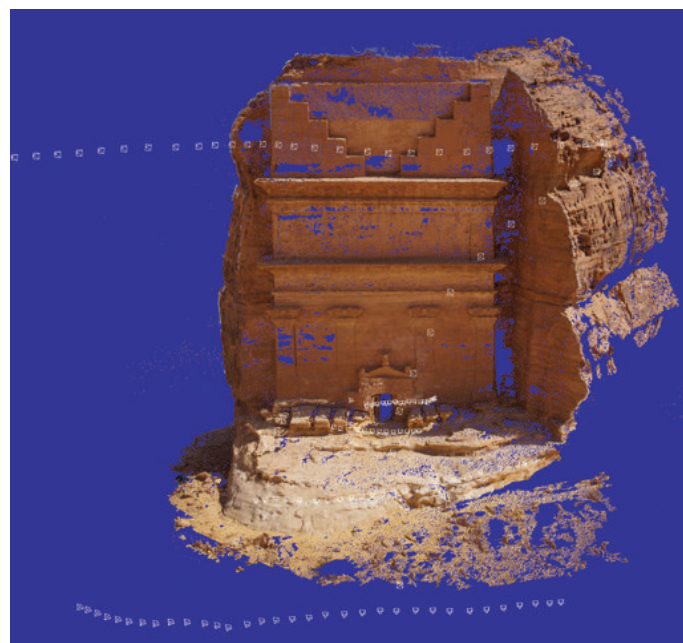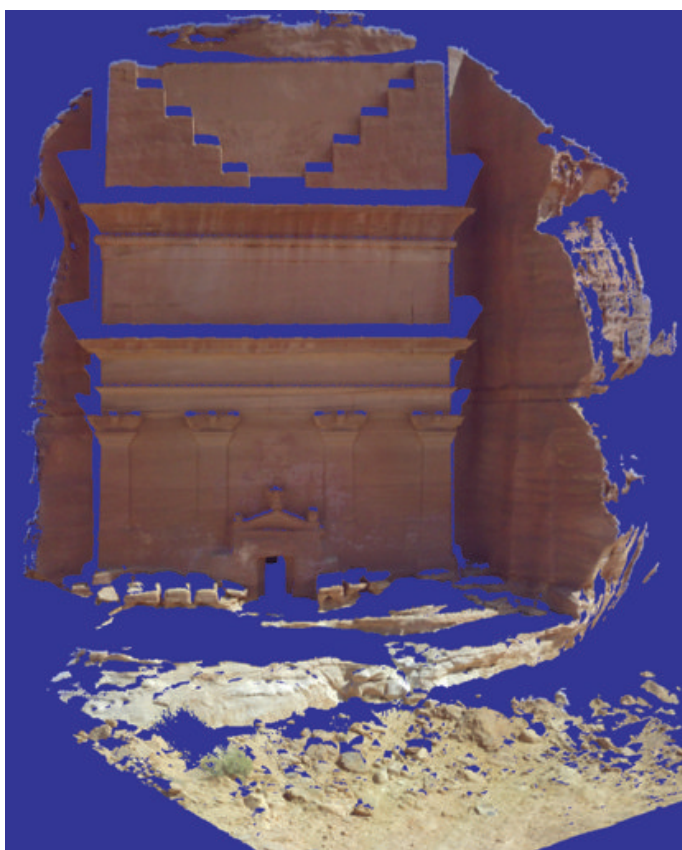

We use a technique from the field of computer vision called Structure from Motion (SfM) to do the first stage of 3D reconstruction. Structure from Motion refers to the method of extracting a 3D structure from many overlapping digital images. Beginning in the twenty-first century, SfM emerged as a new photogrammetric technique for 3D reconstruction that uses robust computer vision algorithms that automatically detect matching features in images (SIFT: Lowe 2004; Wu 2007) and efficiently compute camera intrinsic parameters using a least squares approximation called Bundle Adjustment (Brown and Lowe 2005; Hartley and Zisserman 2003; Snavely 2006; Wu 2011). SfM reconstructs a sparse point cloud and calculates camera positions that allow the computation of dense point clouds and triangulated meshes using Multi-View Stereopsis (Furukawa and Ponce 2007; Hartley and Zisserman 2003). Rather than standing in a fixed position and capturing 3D data, SfM algorithms use a change in camera position for each image to find the distance (motion) between them and at the same time triangulate

the 3D positions of pixels matched in overlapping images. The more motion and movement around the site, the more complete the 3D model becomes. The collection of matched pixels and their calculated 3D positions become a cloud of millions of 3D points, called a point cloud. From a distance the point cloud appears as a solid model similar to 3D models seen in CAD programs or video games, but as you zoom in it becomes
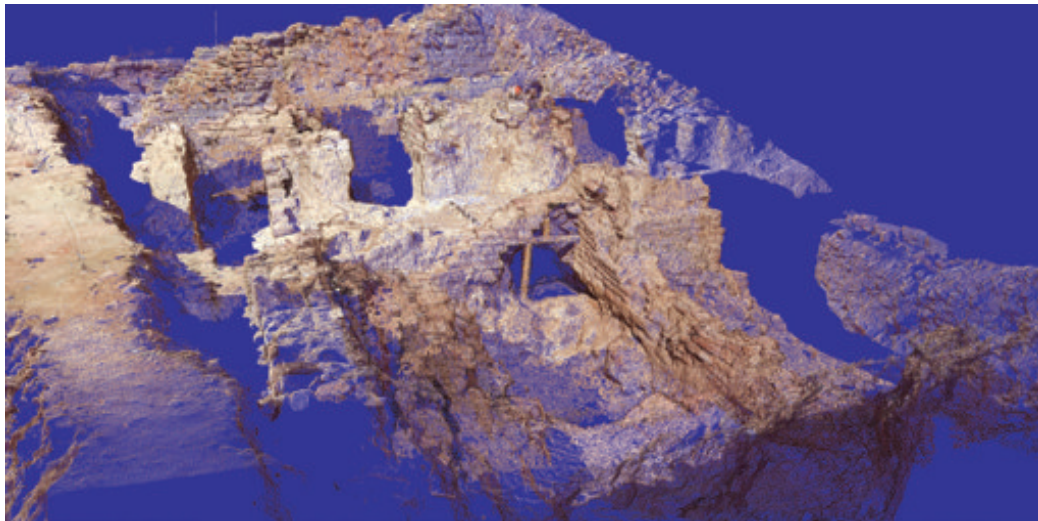
Figure 4 (above). Screenshot of SfM point cloud merged with LiDAR scan using an algorithm to detect spherical markers. The red sphere represents the calculated sphere radius from its computed center. We use multiple spheres placed in the SfM and LiDAR scans to merge the two scanning technologies together. Courtesy of N. Smith.
Figure 5 (below). UAV systems used for aerial scanning. On the left a DJI F450 quad-copter. On the right 3DR Robotics Y6 with APM and Gimbal mounted Sony Nex-7. Ancient Dedan excavations and al-Ula mountain escarpment in background. Photograph by L. Passone.

clear it is actually a collection of millions of points. We use several different algorithms to combine these point clouds from the air, the ground and the laser scanner to create a complete scan of the site (fig. 4). The combination of the software algorithms and the UAV allow us to comprehensively capture the site and reconstruct it in 3D with proper scale and orientation representing its structure in the real world. Later as the point cloud is cleaned and processed it can be turned into a solid model for CAD programs. Although the resolution of SfM point clouds is much lower than a LiDAR laser scan, it is much faster, easier to perform, and vastly more accurate than past archaeological methods that relied on surveyors' illustrated plans. The combination of the two technologies allows us to take advantage of both methods strong points.

Integrated 3D Scanning Results: al-Ula

In the field, we have three teams working simultaneously to run the LiDAR scanner, plan flight missions and fly the UAV, and a third to take detailed terrestrial SfM capture. At the end of the day the massive datasets generated can be merged within the same 3D space to create a comprehensive and accurate 3D reconstruction.

In al-Ula we used a Faro FOCUS3D LiDAR scanner. It is possible to capture within one day the main section of a large excavation area (50 x 50 m), but not the small interior rooms, narrow excavation trenches, tall structures, and other highly occlusive areas of a site. In many cases, these areas cannot accommodate or be adequately reached by the terrestrial LiDAR scanner. The remaining highly occluded areas are captured using terrestrial and airborne SfM. Terrestrial SfM also allows us to take close up captures of important areas that cannot be reached using LiDAR or captured with a high enough resolution from the air. The closer the camera is to the area of capture the higher the density of the point cloud.

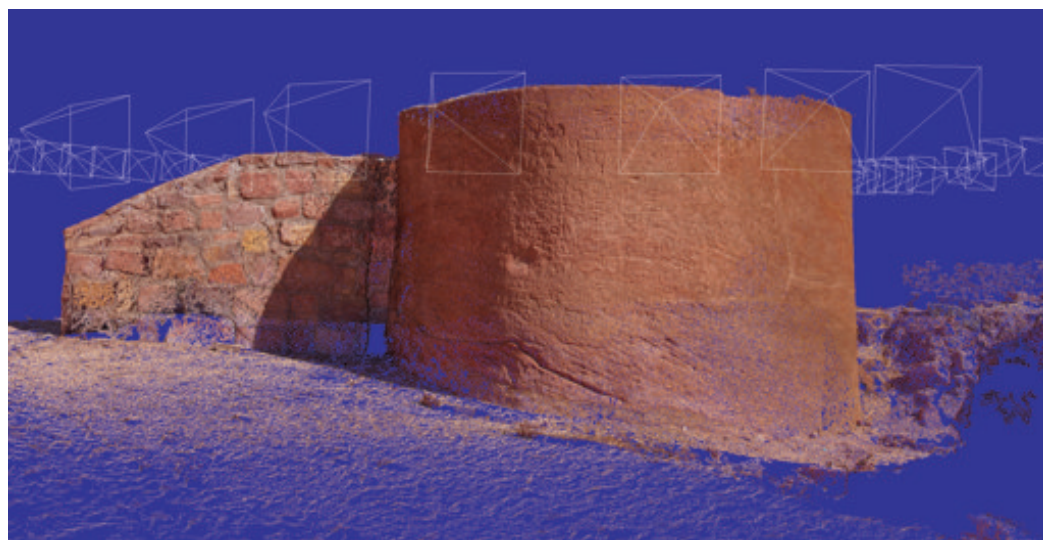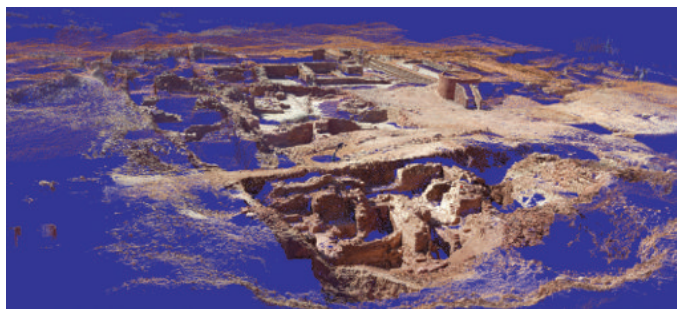When we arrived at the archaeological site of ancient

Dedan we were amazed at the massive size of the settlement. In comparison to the area excavated, 80% of the settlement still remains untouched. We decided to focus our scanning on the two main portions of the southern excavations. LiDAR scanning was conducted on only the northern side of the site. We would have to depend on the terrestrial and aerial SfM to fill in the majority of the excavations occluded by the closest walls (see fig. 2). With the terrestrial SfM we traversed around the entire excavation area. As a close-up, the cistern was captured (fig. 7). The close-up scan of the ancient basin was high enough resolution to identify the texture of the sandstone and the carved Arabic graffiti made by modern visitors.

It was not until mid-afternoon as the sun began to set that the wind died down long enough to safely fly over the site. Two UAV systems assembled by the team were employed for airborne SfM: a DJI Flamewheel F450 quad-copter mounted with a Canon S90 (10MP) and a 3DR Robotics Y6 co-axial hexa-copter gimbal mounted with a Sony Nex-7 (24MP) (fig. 5). Low-altitude scanning (30–100 m) is possible
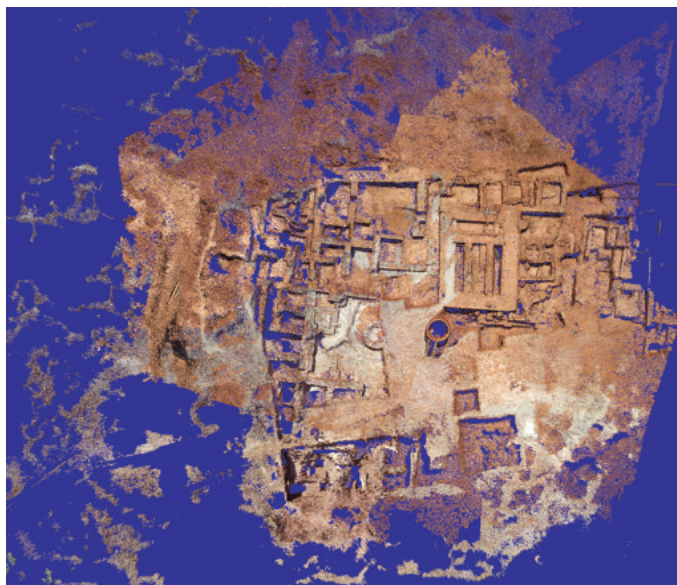
Figure 6. Final registered point cloud model of the Dedan southern excavation area combining LiDAR, terrestrial SfM, and aerial SfM. Top view (above); side view (below). Courtesy of N. Smith.

with multirotor copters since they can fly at a steady pace of 2.5–3.0 m/s maintaining a fixed altitude insuring a significant amount of overlap of sharp images. Our multirotors can fly between 7–9 minutes at a time and can cover within this time one kilometer. The low altitude and steady speed is sufficient to capture most of any large site within only a morning of scanning. Two short flights were made but within this short amount of time we were able to capture the western and eastern halves of the excavation. The aerial SfM reconstructed the entire excavation area from one end to the other. When combined with the LiDAR and terrestrial SfM we were able to situate all the scans in one global system (see fig. 6).

The second area scanned was the lion tombs' carvings (fig. 8). A series of switch back carved steps lead as a procession up to the lion tombs' cliff face. Although we had intended to use the LiDAR scanner, there was no sufficient place to setup the tripod and expect to capture the lion carvings and the tombs. However, we were able to very carefully walk along the edge to take close-ups of the tombs and the carved lions using terrestrial SfM. As the majority of our team climbed up to the cliff, we could hear the buzzing sound of the UAV as it approached from half a kilometer away preparing to capture the entire cliff face, stairway, and terrain below. In just three minutes the UAV was able to capture 44 images that could be reconstructed into a dense 3D point cloud of the lion tombs. With the combined terrestrial SfM we were able to both capture the entire cliff face and the detailed lion carvings.

Comprehensive capture of highly occluded sites is possi-

Figure 7. SfM model of Lihyanite cistern. Courtesy of N. Smith.

ble when SfM and LiDAR are integrated. The results from the expedition to al-Ula demonstrates that the combination of these integrated scanning techniques can within a short amount of time capture complex areas with survey precision measurement. In the two days of the project four areas were systematically captured and have been presented here. Over the next several years these non-invasive 3D scanning techniques will be applied in order to digitally preserve these sites as they are excavated, document the inevitable decay of carvings and structures over time, and provide objective datasets for future analysis and visualization.

Figure 8. Aerial view of lion tombs carved into Jabal Dedan captured using UAV system. Courtesy of N. Smith.

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