Aerial Robotic and Remote Sensing Support to Archeological Discovery in the Etruscan and Roman site of Vulci, Italy

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Abstract

During the summers of 2016 and 2017, a series of Unoccupied Aircraft System (UAS, aka drone) missions were flown over the Vulci plateau, an archaeological relevant site near Rome, Italy. The city of Vulci played a prominent role in Italian history and remains a pivotal piece in understanding the physical and social changes that occurred for both Etruscan and Roman cultures between ~9th century BCE and the ~4th century CE. Given the temporal and financial costs of conducting traditional archaeological excavation on a city-wide scale, remote sensing provides a practical and effective method of collecting data that can give archaeologists a crucial perspective on the remains that lie beneath the surface. The UAS flights were conducted using fixed wing drones equipped with optical (RGB), red edge (RE) and near infrared (NIR) sensors. The present dataset provides raw geolocated images and processed geospatial products (orthomosaics, digital elevation models, and reflectance maps) for both survey years and all sensors. These data products are supplemented with information on individual flight dates, areal coverages, image processing workflows, and associated details on spatial accuracy and resolution. These data will expand the potential for new discoveries in this location through direct access to high quality geospatial information.

Background & Summary

As a site that was continuously occupied for over a millennium, Vulci remains a pivotal piece in understanding the physical and social changes for both the Etruscan and Roman cultures between the ~9th century BCE and the ~4th century CE. Vulci, located in modern day Montalto di Castro, Italy, was founded as an urban center by the Etruscans during a period of urbanization in the 9th century BCE.

The Etruscans were a civilization which predate the founding of Rome and occupied central and parts of northern Italy (Figure 1). They maintained significant maritime control over the Tyrrhenian Sea and conducted trade across the Mediterranean. The development of Rome and their Empire often overshadows the Etruscans; however, it is important to note that the Etruscans' culture and advancements were highly influential in the foundation and development of Roman culture.

Etruscans were connected through shared cultural language and religious beliefs but were structured around a city-state configuration, which allowed each city to maintain their own spatial, economic, and political spheres. The only known multi-city entity was the League of Twelve Cities, which was a religious organization made up of the most influential Etruscan cities which held religious significance but no political power. Vulci was a member of this

League and became an economic powerhouse in Southern Etruria. The northern-most city in the area of Southern Etruria, Vulci was located on a naturally defensible plateau with the Fiora River bordering the eastern side. This traversable waterway provided security, clean water, and easy access to the sea. Vulci's port, Regisvilla, allowed for significant trade and facilitated the city's rise in power. In this position, Vulci acted as a distribution center for imported goods and trade opportunities for inland cities.

The city continued to grow, although the specifics of Vulci's urban area were largely speculative until recent studies (such as this one) were able to offer new insights. The downfall of the Etruscans came after over a century of struggle against the Romans. The success of early Roman expansion over Etruria was aided through the individual nature of Etruscan cities. Etruscan cities, used to fighting over power even with each other and standing independently, joined forces too late to prevent their downfall. In 280 BCE, towards the end of the Roman conquest of Etruria, Vulci made a final stand alongside Volsinii, a prominent inland city and the seat of the League of Twelve Cities. They were thoroughly defeated and recorded as conquered at this time in Roman records, but the treatment of each city varied greatly. Vulci is a particularly important city because it survived Roman expansion and even underwent a later revitalization while others, like Volsinii, had their population enslaved and the city itself burned to the ground and abandoned. While many of the smaller cities and towns within Vulci's territory were abandoned, such as Doganella's fate, Vulci remained intact with an influx of wealth and development of the city during the early Imperial Period.

Scholars could gain a more complete understanding of this Etruscan-Roman transition and cultural developments through an examination of Vulci on a city-wide level. While Vulci was not built up during modern times and is today protected as an archaeological park, traditional archaeological excavation would be too financially and temporally costly to uncover enough features to support a city-scale examination. Therefore, such a study is only possible with alternative remote sensing methods, such as aerial imagery.

While the final products from the Duke University Marine Robotics and Remote Sensing (MaRRS) Lab and the Vulci 3000 archaeological team support new archaeological investigation of Vulci from a crucial perspective, there are endless possibilities for additional uses of these datasets. This effort aims to provide public access to organized datasets by flight or final products such as the orthomosaics. Access to these various levels of data allows for a broader range of researchers in more areas of interest to utilize this data for additional studies.

Methods

Overview. During the summers of 2016 and 2017, the Duke University Marine Laboratory Marine Robotics and Remote Sensing (MaRRS) Lab collaborated with Dr. Maurizio Forte to fly extensive aerial surveys of Vulci's main urban archaeological site on the plateau as well as the surrounding landscape with auxiliary archaeological sites. Remote piloting an eBee senseFly drone, flights collected near infrared (NIR), red edge (RE), and red-green-blue (RGB) geolocated images. The thousands of resulting images were used to create high-resolution orthomosaics, 3d point clouds, and reflectance maps.

Location. Vulci is situated on a plateau about 100 km north of Rome following the coast. The city was directly connected to the sea by the Fiora River, which bordered the eastern side of the plateau. Unlike the low water levels of the Fiora River today, the river's water level was substantial enough for the Etruscans to use it for transportation and trade. Vulci's strategic position during the Etruscan period paved the way for it to become a powerful, economic trade hub, utilizing their connection to and control over coastal area using their port city of Regisvilla as well as inland areas accessible through a well-developed road-system.

The ancient city can be found on the outskirts of modern-day Montalto di Castro, Italy surrounded by farmland. The plateau is protected by the Ministry of Culture as a nature and archaeological park, although parts of the plateau have been used for grazing of animals or farming. The southern portion of the site is leased out for cattle grazing while adjacent southern corners are owned and utilized by local farmers, mostly for wheat crops.

The city expanded over centuries of growth to eventually have five access gates: North, East, Southeast, South, and West (Figure 2). The West and East gates were likely early access points and are connected by the main *decumanus* (major east-west road of the city). The Northern Acropolis and the Southern Acropolis were separated early on with ditches from the main urban areas for religious reasons. Necropolises can be found to the north, east, and southeast of the plateau, outside of the city walls.

As much of the site remains unexcavated, there are only seven visible features in Vulci's urban center (aside from the city walls and gates). These buildings include (from west to east): the Arch of Publius Sulpicius Mundus, Edificio in Laterizio, Great Temple, Edificio Absidato, excavation site of the Vulci 3000 project, House of Cryptoportico, and House of the Fisherman. These known features are clustered in the center of the city, close to the *decumanus* and area which became the heart of the city likely around the 6th century B.C.E. Of these structures, only the Great Temple, the House of the Fisherman, and some features uncovered in the excavation by the Vulci 3000 project can be dated back to the Etruscans. The other features date to after the Roman conquest and occupation of the city or later (Figure 3).

Unoccupied aircraft systems. In 2016, a senseFly eBee Classic aircraft (Figure 4) was employed as a modular fixed-wing unoccupied aircraft system (UAS) produced by the Swiss company senseFly (owned by AgEagle in the U.S. as of January 2023). The eBee has a light-weight foam "flying wing" airframe powered by a single rear-mounted brushless electric motor and a 2150 mah lithium polymer battery. Two elevons (i.e., combined elevator and ailerons) provide the flight control surfaces, and each elevon is controlled by one servo embedded in the fuselage. The aircraft has a wingspan of 96cm, weight of 0.7kg, and the maximum flight times are typically 20-35 minutes, landing with at least 30% battery capacity remaining. The mission payloads were Canon S110 NIR, RE, and RGB cameras modified with an umbilical to connect to the eBee aircraft. Images were stored on an internal SD card that could be removed from the camera for image processing. During flight, the eBee autopilot triggered the camera through the umbilical according to mission planning parameters, with the aircraft compensating for environmental factors like flight level winds. A calibration card was used for the 2017 NIR flights.

In 2017, a more advanced senseFly product, the eBee Plus aircraft (Figure 4), was employed with the same sensors from the 2016 surveys. The eBee Plus has the same flying wing configuration but is larger than the eBee Classic with a wing span of 110cm and weight of 1.1kg. With the larger wing and 4900 mah lithium polymer battery, maximum flight times are typically 30-45 minutes. The eBee Plus also has real-time kinematic (RTK) navigation accuracy, a capability that was not available for the 2016 aerial surveys.

Takeoff and retrieval. For the aerial missions in Vulci, there were many open areas for launch and recovery of the aircraft, and obstacles were easily avoided during the mission planning process. The aircraft was launched by hand, followed a pre-programmed flight path, and recovered after a linear approach/landing at a predetermined 10m radius region. The aircraft landed at a slow airspeed into the wind and there was no landing damage during the 2016 and 2017 missions in Vulci.

Flight planning and method of operation. The eBee aircraft was programmed with senseFly eMotion ground control software to follow 3-dimensional flight paths that were uploaded to an on-board autopilot via datalink. The aircraft followed these pre-programmed flight paths for all flights and was guided by a precision GPS sensor, a high-resolution barometer, ground-sensing camera, and airspeed indicator. Failsafe logic within the autopilot was set to return the UAS to the landing zone if it experienced anomalies in aircraft performance, sensor performance, or extreme wind conditions in any of the missions. All flight data were telemetered to the operator over UHF frequencies in real-time.

The missions were planned to achieve 3 cm per pixel ground sampling distance (GSD) which required an altitude of 85m above takeoff elevation for the flights, and the planner used lateral overlap of 75% and longitudinal overlap of 75%. Figure 5 provides a representative flight plan for the southern area of the Vulci plateau. The depicted flight plan projected a 27 minute and 53 second flight time, 20.6 km flight distance, 38 hectare flight coverage, 14 flight lines, and 30 m line spacing. It took 8-10 eBee Classic missions per spectral camera type to cover the Vulci plateau, northern necropolis, and Cucumella necropolis (a little over 3 square km) in 2016. The flight plan outer circle in Figure 5 is an operator-controlled geo-fence. If the flight plan penetrates the geo-fence, the aircraft will hold until the flight plan is altered or the geofence radius is extended. If the aircraft penetrates the geo-fence during the mission, it will automatically return home (unless given further instructions by the operator).

Permits and regulations. Since the Vulci plateau is within Italian restricted airspace, Dr. Forte coordinated with Italian aviation authorities prior to flight. The officials were provided with specifications for the senseFly eBee aircraft, and the operator's FAA remote pilot certification, aircraft qualifications, and flight currency. The missions were flown within Italian Civil Aviation Authority and International Civil Aviation Organization norms. The flight plans were included in the scientific archaeological permit of the Vulci 3000 Project (released by the Ministry of Culture).

Mission overview. The deployment objective was to acquire overlapped high-resolution NIR, RE, and RGB raw imagery that, when merged with eBee flight log data, could be geo-tagged and processed using structure-from-motion techniques. We prioritized NIR flights, then RE flights, and finally RGB (as the lowest priority). On July 4, 2016, NIR flights were conducted in the central and north regions of the Vulci plateau. On July 5th, NIR flights completed the NIR aerial survey of the plateau and northern necropolis. On the same day, there were additional multi-spectral flights (NIR, RE, and RGB) in the area of Cuccumella tumulus. On July 6th, RE flights were conducted in the central part of the plateau and multi-spectral flights in the area of the François Tomb. Flights on July 7th completed the RE aerial survey of the plateau and northern necropolis, and additional multi-spectral flights focused on the Duke Vulci 3000 excavation site near the middle of the park. Finally, on July 8th, flights were conducted to complete an RGB aerial survey of the plateau and northern necropolis.

During the 2017 missions, the remote pilot experienced challenges with the aircraft barometer, greatly limiting the area of the surveys. Despite these challenges, there were significantly expanded surveys of the area in and around the northern necropolis and Cuccumella tumulus (Eastern necropoleis). With the eBee Plus RTK precision, ground sampling distance was reduced from an impressive 3.62 – 3.65 cm per pixel in 2016 to 2.76 – 2.87 cm per pixel in 2017. Detailed processing analysis for both years can be found in the Quality Reports.

Upon return to the U.S., the objective of post-mission processing was to provide multi-spectral geolocated imagery, orthomosaics, 3d point clouds, and reflectance maps of the site by using Pix4Dmapper software. Pix4Dmapper has numerous processing options in three categories: 1) initial processing to check for data quality 2) construction of point clouds and 3D textured mesh and 3) building a digital surface model, orthomosaic, and if desired, reflectance maps. Altogether, there are three large-scale complete multi-spectral datasets for the Vulci plateau, northern necropolis, and Cucumella tumulus.

Data Records

Post-flight processing. Table 1 provides a listing of the daily flights in 2016 and 2017. At the end of each flying day, the remote pilot backed-up the camera SD card, aircraft flight log, and ground control station log. Next, the operator used eMotion flight data manager to conduct initial processing that included geotagging the flight images, producing a .kml file so the flight path could be displayed on Google Earth, building a .txt file with each image and its geocoordinates, and developing a specially formatted Pix4D file to expedite more rigorous processing using Pix4Dmapper. Full processing did not occur until return to the Duke Marine Lab.

Date	Flt #	Flt Log	Sensor	T/O Time (UTC)	Flt Time	Image #s	Total # of Images	Folder
7/4/2016	1	207	NIR	7:31:59	0:28:58	2791-3122	332	2016-07-04_Central West NIR
	2	208	NIR	8:08:22	0:28:11	3123-3447	325	2016-07-04_Central East NIR
	3	209	NIR	8:36:03	0:30:22	3448-3791	344	2016-07-04_Central South NIR
	4	210	NIR	12:05:33	0:30:55	3792-4145	354	2016-07-04_North NIR
	5	211	NIR	13:03:58	0:23:19	4146-4407	262	2016-07-04_Central Far East NIR
7/5/2016	1	212	NIR	6:12:04	0:31:06	4408-4765	358	2016-07-05_Cucumella NIR
	2	213	RE	6:42:00	0:26:37	4922-5219	298	2016-07-05_Cucumella RE 1
	5	216	RGB	7:55:23	0:31:26	2968-3312	345	2016-07-05_Cucumella RGB 1
	6	217	RE	8:29:24	0:19:48	5220-5426	207	2016-07-05_Cucumella RE 2
	7	218	NIR	13:09:09	0:30:03	4766-5107	342	2016-07-05_South SE NIR
	8	219	NIR	13:47:21	0:26:19	5108-5411	304	2016-07-05_South SW NIR
	9	220	NIR	14:18:36	0:23:12	5412-5652	241	2016-07-05_South S Tip NIR
7/6/2016	1	221	RE	5:58:32	0:29:07	5427-5754	328	2016-07-06_Central West RE
	2	222	RE	6:28:16	0:29:07	5755-6093	339	2016-07-06_Central East RE
	3	223	RE	7:04:58	0:30:48	6094-6426	333	2016-07-06_Central South RE
	4	224	RE	9:20:04	0:30:43	6427-6764	338	2016-07-06_Central Far East RE
	5	225	RE	14:06:00	0:11:36	6765-6873	109	016-07-06_Francois Tomb RE
	6	226	NIR	14:22:49	0:11:23	5653-5764	112	22016-07-06_Francois Tomb NIR
	7	227	RGB	14:40:17	0:11:49	3313-3424	112	2016-07-06_Francois Tomb RGB
7/7/2016	1	228	RE	6:19:02	0:31:08	6874-7236	363	2016-07-07_Central South East RE

	2	229	RE	6:49:45	0:30:23	7237-7584	348	2016-07-07_Central South West RE
	3	230	RE	7:27:08	0:29:09	7585-7897	313	2016-07-07_Central South RE
	4	231	RE	9:27:42	0:29:14	7898-8227	330	2016-07-07_Central North RE
	6	233	RE	14:32:49	0:07:40	8228-8285	58	2016-07-07_Excavation RE
	7	234	RGB	14:42:13	0:07:47	3583-3640	58	2016-07-07_Excavation RGB
	8	235	NIR	14:52:52	0:08:00	5765-5825	61	2016-07-07_Excavation NIR
7/8/2016	1	236	RGB	6:29:44	0:22:07	3641-3903	263	2016-07-08_Plateau RGB N1 85m
	2	237	RGB	7:01:18	0:20:53	3904-4142	239	2016-07-08_Plateau RGB N2 85m
	3	238	RGB	7:57:30	0:14:57	4143-4317	175	2016-07-08_Plateau RGB NC1 85m
	4	239	RGB	8:19:41	0:29:22	4318-4687	370	2016-07-08_Plateau RGB NC2 85m
	5	240	RGB	9:38:07	0:23:38	4688-4945	258	2016-07-08_Plateau RGB C1 85m
	6	241	RGB	10:03:11	0:23:25	4946-5240	295	2016-07-08_Plateau RGB C2 85m
	7	242	RGB	12:57:37	0:23:43	5241-5527	287	2016-07-08_Plateau RGB CS 85m
	8	243	RGB	13:30:59	0:17:41	5528-5730	203	2016-07-08_Plateau RGB S1 85m
	9	244	RGB	13:53:14	0:14:16	5731-5893	163	2016-07-08_Plateau RGB S2 85m
7/22/2017	1	23	NIR	9:57:16	0:40:26	2719-3125	407	170722VulciNIRF1
7/24/2017	1	24	NIR	7:53:54	0:34:32	3126-3538	413	170724VulciNIRF1
7/25/2017	1	25	NIR	7:44:58	0:41:59	3539-4000	462	170725VulciNIRF1
	3	27	NIR	9:11:56	0:25:00	4019-4289	271	170725VulciNIRF2
	4	28	NIR	9:46:52	0:18:05	4290-4464	175	170725VulciNIRF3

Table 1. Vulci daily flights from 2016 and 2017 delineated by day, number of flights that day, flight log number, sensor type, takeoff time (UTC), flight time, image numbers, total number of images, and folder where archived flight data is located.
*Missing flight numbers are purposeful; some flight images were not useful to orthomosaic reconstruction and thus were not included.
*Flights over François Tomb (7/6/2016) and the Excavation site (7/7/2016) were flown at lower altitudes/higher resolution; the images from these flights are included but are not included in image processing products.

Data Archive Overview

The data provided in this archive include geolocated JPG images, image processing products, and accessory information needed to understand and use these data. The archive is organized into the following folders with the following contents:

The **Overview** folder provides a written overview of the dataset's historical context, collection purpose, collection methods, and archaeological applications.

The **Daily Flights Information** folder provides supplemental information for each flight conducted at the Vulci plateau and Cuccumella necropolis areas in 2016 and 2017. Each flight has a folder named with the date of the flight, area flown, and sensor used (see Table 1 above for full flight list). Each of these flight folders contains flight logs (.efl and .bbx files), location information for each image taken in flight (.txt file), and flight paths and locations of each JPG from the flight (.kml file).

The **Red Green Blue Data** folder provides a consolidation of all red-green-blue (RGB) images captured and products generated for the Vulci plateau and Eastern necropoleis areas in 2016. This folder contains all RGB images captured (geolocated .jpg files), all RGB products generated from Pix4D image processing software (orthomosaics and digital elevation models (geolocated .tif files); 3D mesh and point cloud data (geolocated .las files)), and quality information about the image processing (quality report .pdf file).

The **Near Infrared Data** folder provides a consolidation of all near infrared (NIR) images captured and products generated for the Vulci plateau, Cuccumella and Eastern necropoleis areas in 2016 and 2017. This folder contains all NIR images captured (geolocated .jpg files), all NIR products generated from Pix4D image processing software (orthomosaics and digital elevation models (geolocated .tif files); 3D mesh and point cloud data (geolocated .las files)), and quality information about the image processing (quality report .pdf file).

The **Red Edge Data** folder provides a consolidation of all red edge (RE) images captured and products generated for the Vulci plateau and Eastern necropoleis areas in 2016. This folder contains all RE images captured (geolocated .jpg files), all NIR products generated from Pix4D image processing software (orthomosaics and digital elevation models (geolocated .tif files); 3D mesh and point cloud data (geolocated .las files)), and quality information about the image processing (quality report .pdf file).

Technical Validation

During 2016 and 2017 post-mission processing, Pix4D software provided rigorous technical validation resulting in a comprehensive quality report. For the 2017 missions, an image of a calibration card was captured before each multi-spectral mission, and this image was used during post-mission processing to compensate for lighting changes in the red, green, RE, and NIR spectrums. The processing of the 2017 missions also used post-processed kinematic navigation corrections by referencing the Terni, Italy base station (ID: UN TR00ITA). Table 2 provides metadata from the Vulci quality reports. More detailed dataset quality information is available in pdf format under the 1_initial/report subfolder for each spectral product.

Year	Sensor	Survey Area	Avg GSD (cm)	Area Covered (ha)	Total # of Images	Median Keypoints per Image	Median Matches per Image	Folder
2016	NIR	Plateau, Northern necropolis, Cucumella	3.65	313.665	2,862	42,496	10,740.50	Near Infrared Data 2016
	RE	Plateau, Northern necropolis, Cucumella	3.62	310.852	3,197	61,880	20,355.40	Red Edge Data (2016)
	RGB	Plateau, Northern necropolis, Cucumella	3.62	308.657	2,910	67,705	12,567.50	Red Green Blue Data (2016)
2017	NIR	Expanded Northern necropolis	2.76	96.5276	859	66,723	3,589.16	Near Infrared Data 2017
	NIR	Expanded Cucumella	2.87	90.9875	869	67,646	3,852.49	Near Infrared Data 2017

Table 2. Processed Vulci metadata from 2016 and 2017 quality reports that reflects sensor type, locations covered, average ground sampling distances, area covered, total images per spectral sensor, median number of keypoints per image, median number of matches per image, and the folder in the archives where the mission data is located.

Usage Notes

These datasets have been used extensively by Dr. Forte's Vulci 3000 team as well as by McCusker as one of many datasets used in a dissertation focused on Vulci's urban morphology. Representative analysis is provided in Figures 6 and 7. Complete works can be found through Duke University. If this aerial-based analysis is examined alongside results from other remote sensing technologies and historical records, even greater and more precise conclusions can be reached about the features and use of space in the city (Forte et al., 2022; Johnston et al., 2020; LoPiano & McCusker, 2020; McCusker, 2021).

Figures

Figure 1. This map contextualizes the location of Vulci and other major Etruscan cities, as well as illustrates the impressive expansion of Etruscan territory (map from McCusker 2021).

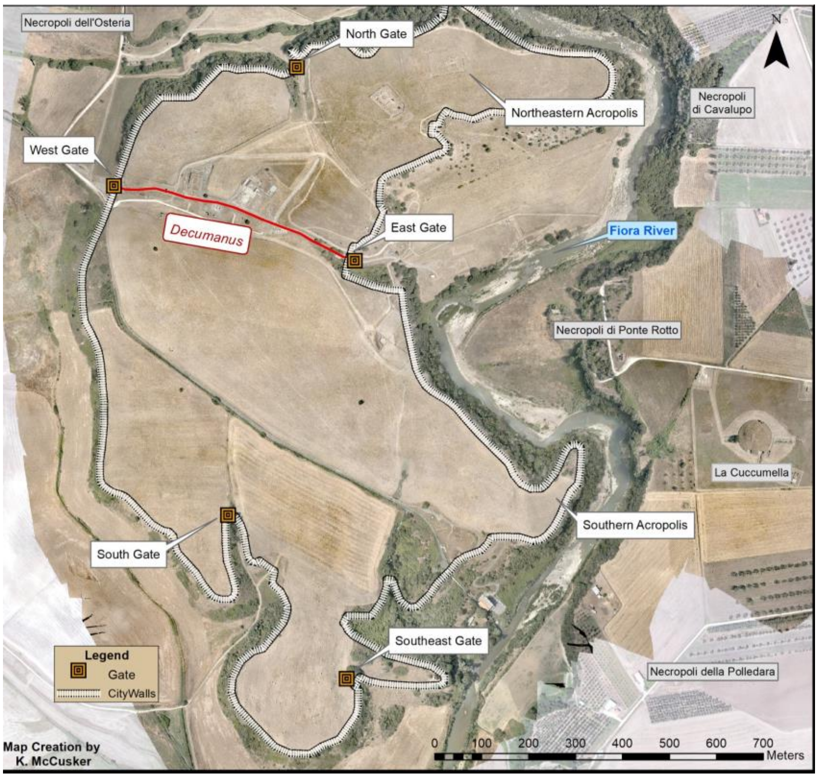

Figure 2. View of the entire Vulci plateau showing the location of major features, including city gates, walls, and necropolises (map from McCusker 2021).

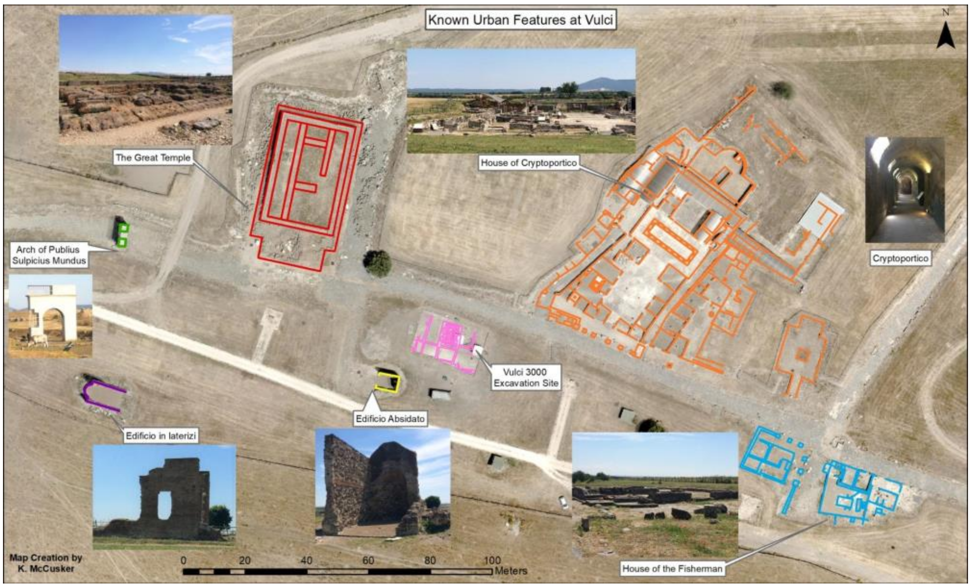

Figure 3. View of the Arch of Publius Sulpicius Mundus, Edificio in Laterizio, Great Temple, Edificio Absidato, excavation site of the Vulci 3000 project, House of Cryptoportico, and House of the Fisherman. These known features are clustered in the center of the city, close to the *decumanus* and area which became the heart of the city likely around the 6th century B.C.E. Of these structures, only the Great Temple, the House of the Fisherman, and some features uncovered in the excavation by the Vulci 3000 project can be dated back to the Etruscans (map from McCusker 2021).

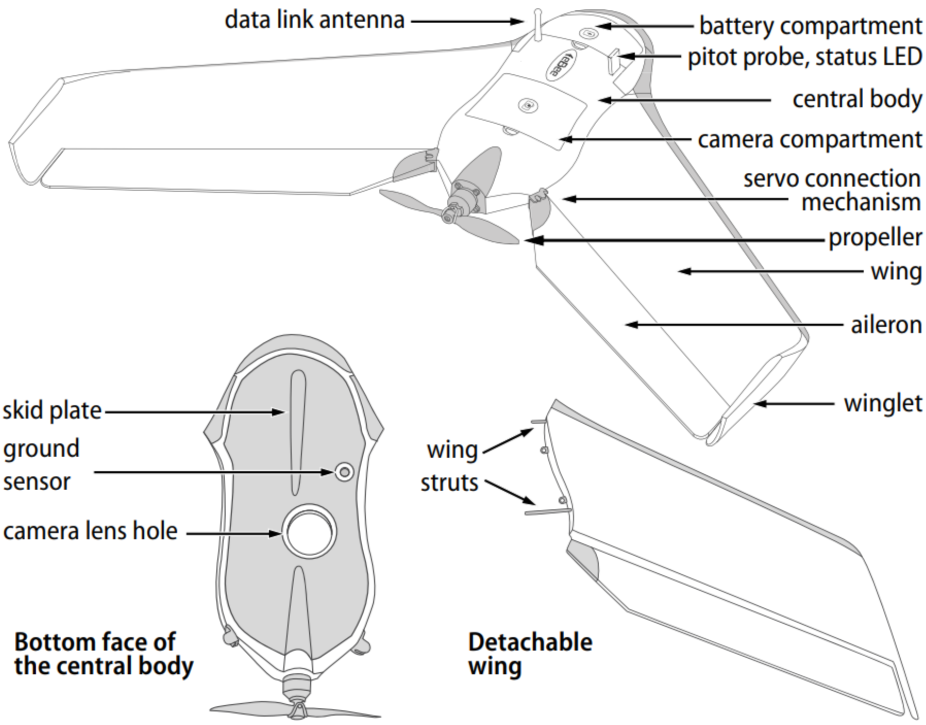

Figure 4. Components of eBee Classic flying wing (diagram credit: eBee Classic Drone User Manual)

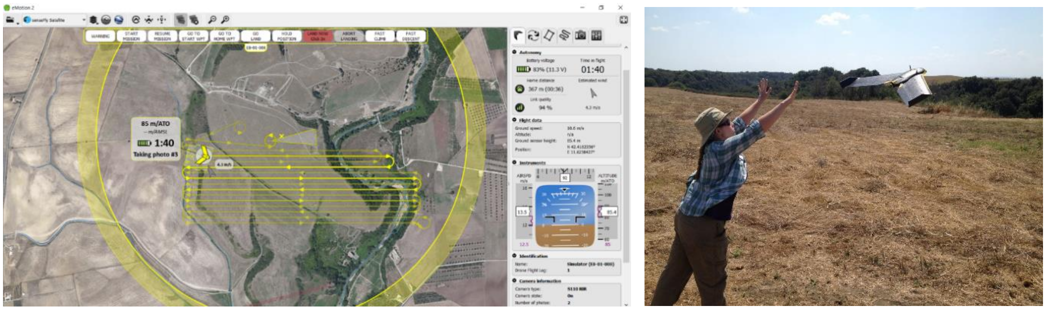

Figure 5. A representative flight plan in the southern Vulci plateau (left) and Duke University archeologist and PhD student Katie McCusker launches an eBee in the southern part of the Vulci plateau in 2016 (right). The flight plan projected a 27 minute and 53 second flight time, 20.6 km flight distance, 38 hectare flight coverage, 14 flight lines, and 30 m line spacing. The flight plan outer circle is an operator-controlled geo-fence that defines the maximum vertical and horizontal extent of the flight area.

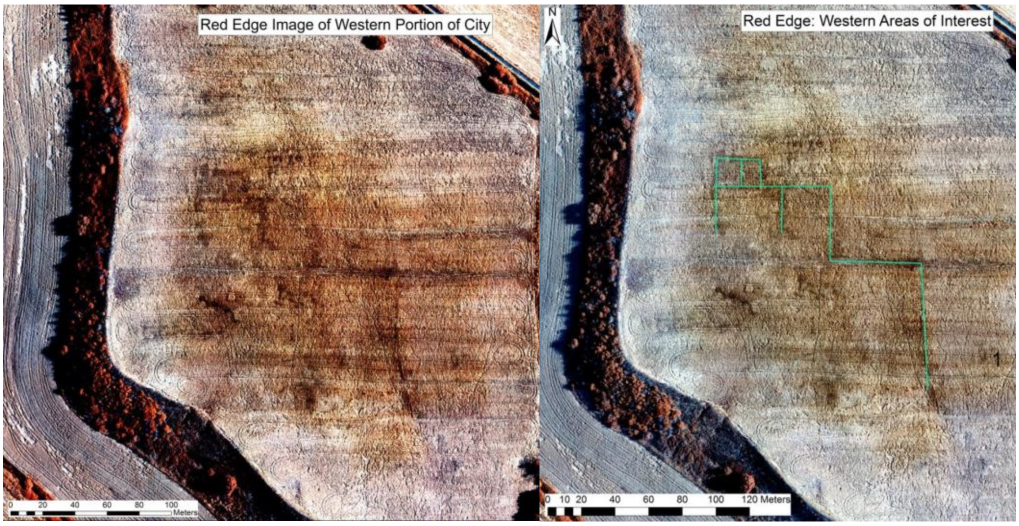

Figure 6. The red edge orthomosaics reveal indications of a large structure in the southwest corner of the city (images with color band stretch) (maps from McCusker 2021).

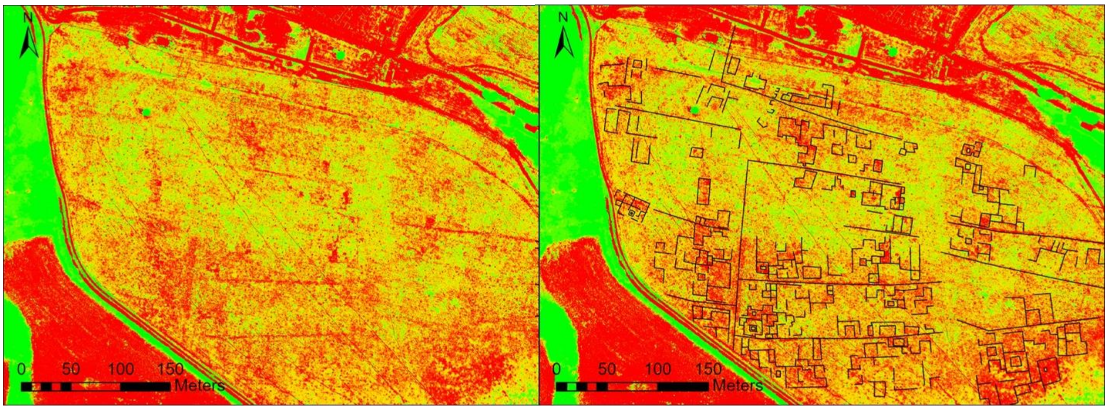

Figure 7. A comparison of the NDVI of the central-southern area of Vulci without (left) and with (right) feature interpretation solely based on the new aerial data sets (maps from McCusker 2021).

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