ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

THREE-DIMENSIONAL PHOTOGRAMMETRIC DOCUMENTATION OF CULTURAL HERITAGE: A CASE STUDY IN SAGALASSOS

M.Sc. THESIS

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Department of Geomatic Engineering

Geomatic Engineering Programme

MAY 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KÜLTÜREL MİRASIN FOTOGRAMETRİK YÖNTEMLE ÜÇ BOYUTLU BELGELENMESİ: SAGALASSOS ÖRNEK ÇALIŞMASI

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To whom endeavored,

FOREWORD

I would like to thank to my thesis advisor Prof. Dr. Dursun Zafer ŞEKER who never gave up hope of me and always helped me while preparing this study.
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April 2015

Umut OVALI
Geodesy and Photogrammetry Engineer

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ABBREVIATIONS

AD	**:** Anno Domini
BC	**:** Before Christ
CAD	**:** Computer Aided Design
EDM	**:** Electronic Distance Meter
GCP	**:** Ground Control Point
ICOMOS	**:** International Council on Monuments and Sites
LCD	**:** Liquid-crystal Display
MP	**:** Mega Pixel
MVS	**:** Multi-View Stereo
SfM	**:** Structure From Motion
SIFT	**:** Scale Invariant Feature Transform
TAY	**:** Archaeological Settlements of Tukey
TAYex	**:** TAY Expedition
TLS	**:** Terrestrial Laser Scanning

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THREE-DIMENSIONAL PHOTOGRAMMETRIC DOCUMENTATION OF CULTURAL HERITAGE: A CASE STUDY IN SAGALASSOS

SUMMARY

Anatolia, which occupies most of the territory of the Republic of Turkey, has been considered archaeologically ‘rich’ because it has been inhabited at different times by settlers from both the East and the West. It has been found that 42 different civilizations lived in Anatolia before Ottoman period. Such a richness does not only belong to the Republic of Turkey nor the actual generation, it does belong to the entire humanity. It is of vital importance to document such richness as accurately as possible since it is vulnerable to numerous threats, human or natural. Although it should be transferred to the next generations, it is exposed to destruction by mankind, due to inadequate maintenance, lack of financial and/or human resources, state development projects and armed conflicts.

The ancient Pisidian city of Sagalassos is yet another invaluable reflection of human history. The Catholic University of Leuven (Belgium) is leading an international archaeological excavation project in the ancient city of Sagalassos since 1995. One of the goals of the project is to preserve the archaeological remains which they exposed.

Accurate geographic documentation has always been a crucial scientific component of archaeology. Conventional 2D recording techniques in the form of orthographic drawings and/or photography are being increasingly challenged in the last decade by the three-dimensional methods that offer user friendly, low cost and time efficient solutions. These methods are closely related to the fast developing digital technology. Generated surface model data have the potential to serve multiple functions besides the geographic and metric documentation of the archaeological features. This study presents one of the 3D registration techniques employed in 2013 at the ancient city of Sagalassos, using “Structure from Motion” (SfM) and “Multi-View Stereo” (MVS) algorithms. It specifically focuses on the documentation of exposed fragile architectural remains in a trench, at the end of the excavations. The employed methodology and achieved results are presented and compared to the commonly used other 3D recording techniques. The potential of this 3D method to replace conventional 2D architectural measured drawings is discussed, as well as its capacity to perform as a site management tool for conservation and monitoring. Successful results show that this method can be used for fast and accurate geometric documentation.

KÜLTÜREL MİRASIN FOTOGRAMETRİK YÖNTEMLERLE ÜÇ BOYUTLU BELGELENMESİ: SAGALASSOS ÖRNEK ÇALIŞMASI

ÖZET

Türkiye Cumhuriyeti topraklarının büyük bir kısmını kaplayan Anadolu arkeolojik bağlamda çok zengin topraklara sahiptir. Değişik zaman aralıklarında doğu ve batıdan bir çok uygarlık bu topraklar üzerinde yaşamış ve göçmüşlerdir. Öyle ki; Osmanlı İmparatorluğu dönemi öncesinde kırkiki farklı uygarlığın Anadolu'da yaşadığı bulunmuştur. Bu tarihi zenginlik sadece Türkiye Cumhuriyeti'nin ya da şu anda yaşayan neslin değil, tüm uygarlığın ve gelecek nesillerindir. Bu miras, korunarak sonraki nesillere aktarılması gerekirken insan eliyle yıkıma uğramakta veya doğal tehlikelere karşı korunaksız bırakılmaktadır. Savaşlar, az miktarda finansal kaynaklar, yetersiz bakım çalışmaları, kontrolsüz yapılaşma ve tarım faaliyetleri, devlet marifetiyle düzenlenen alt ve üst yapılar yıkıma neden olan bir kaç örnek olarak gösterilebilir. Bu mirası olabildiğince yüksek doğrulukla belgelemek doğal veya insan kaynaklı tehlikeler göz önüne alındığında son derece önem taşımaktadır.

Antik Pisidya Kenti Sagalassos, Anadolu'da yer almış, insanlık tarihinin paha biçilemez yansımasılarından sadece birisidir. Leuven Katolik Üniversitesi 1995 yılından bu yana Sagalassos Antik Kenti'nde disiplinler arası bir kazı çalışması yürüterek bu zenginliği açığa çıkarmaktadır. Kazı çalışmalarıyla ortaya çıkarılan şehrin korunması projenin önceliklerindendir. Bu bağlamda, koruma çalışmalarının bir parçası olarak belgeleme ve belgeleme için seçilen yöntem son derece önem taşımaktadır.

Doğruluğu yüksek coğrafi belgeleme her zaman arkeolojinin bilimsel açıdan çok önemli bir bileşeni olmuştur. Geleneksel iki boyutlu kaydetme teknikleri ortografik çizimleri ve/veya fotoğrafları kapsamaktadır. Sagalassos Kazı çalışmalarında kullanılan belgeleme yöntemi ise hem geleneksel hem de topografik yöntemleri barındırmaktadır. Mimari çizimleri hem kağıt üzerinde hem de CAD ortamında gerçekleştiren bir ekip, belgelenecek yapının veya objenin büyüklüğüne göre ölçüm yöntemini belirlemektedir: Eğer belgelenecek obje geleneksel ölçüm metoduna daha uygun ise basit ölçme aletleri kullanılarak ölçümler belli bir ölçekte gerçekleştirilir ve daha sonra mevcut çizim taranarak dijital ortamda sayısallaştırmak üzere bir CAD ortamına aktarılır. Eğer belgelenecek alan basit ölçme aletleriyle belgelemek için çok büyük ise topografik ölçme yöntemi uygulanır. Bu yöntemde ölçüm total station aletiyle, yerel veya global bir koordinat sisteminde gerçekleştirilmektedir. Ölçülen noktaların dijital ortama aktarımı son derece kolay olmasından ötürü dijital çizimler daha hızlı gerçekleştirilmektedir. Bu yöntemin ölçüm doğruluğu geleneksel yönteme göre daha yüksektir ve ölçümler çok daha hızlı bir şekilde gerçekleştirilebilmektedir. Son dönemlerde geleneksel belgeleme yöntemlerine rakip olarak kullanımı kolay, doğruluğu yüksek ve hızlı üç boyutlu belgeleme metodları gelişmektedir. Bu yöntemlerden biri lazer tarama yöntemi olup son derece hızlı, detaylı ve doğru üç boyutlu nokta bulutu oluşturmaktadır. Ancak kazı bütçeleri göz önüne alındığında

lazer tarayıcı aletlerini satın almak son derece maliyetli bir harcama olacağı görülmektedir. Bu sebeple bu yöntem arkeolojik sahalardaki açmaların belgelenmesi yerine genellikle büyük ölçekli yapıların üç boyutlu ölçümünü gerçekleştirmek üzere tercih edilmektedir. Bir diğer üç boyutlu belgeleme yöntemi ise dijital fotogrametridir. Fotogrametri belgeleme bağlamında genellikle tek fotoğraf değerlendirmesi yapılarak iki boyutlu cephe çizimleri için kulanılmaktaydı. Ancak dijital teknolojinin gelişmesiyle beraber birden fazla dijital fotoğrafın düşük maliyetli fotogrametrik yazılımlar ile piksel eşleştirme algoritmaları kullanılarak üç boyutlu nokta bulutu yaratmak mümkün hale gelmiştir. Herhangi bir objenin veya alanın çevresinden birbiri ile örtüşen dijital fotoğraflar çekilerek üç boyutlu nokta bulutu, bu nokta bulutunun üçgenlenip fotoğraflardan doku geçirilmesi ile de foto-gerçekçi modeller üretilebilmektedir. Bu model üzerinden alınan orto-imajlar vasıtasıyla geleneksel yöntemlerde olduğu gibi iki boyutlu ortografik çizimler CAD ortamında kolaylıkla gerçekleştirilebilmektedir. Ayrıca üretilen üç boyutlu yüzey verisi coğrafi ve metrik belgelemenin yanında bir çok potansiyel fayda sağlaması beklenmektedir. Üç boyutlu fotogrametrik yöntem diğer metodlara göre, hız, doğruluk, detay ve maliyet parametreleri göz önüne alındığında açmaların ve küçük objelerin belgelenmesi için son derece uygun olduğu görülmektedir.

Bu çalışma, 2013 yılında Sagalassos Antik Kenti'nde gerçekleştirilen kazı çalışmaları sırasında, "Structure from Motion" (SfM) ve "Multi-View Streo" (MVS) algoritmaları kullanan rus ticari yazılımı Agisoft Photoscan ile gerçekleştirilen 3 boyutlu belgeleme tekniğini ele almaktadır. Fotoğraflar Nikon firmasının üretmiş olduğu D5000 model, 12.3 megapiksel, dijital SLR kamera ile çekilmiştir. Kuşbakışı çekimlerin uygun yükseklikten yapılabilmesi amacıyla kamera, 2 metreden 6 metreye kadar ayarlanılabilen bir çubuğa monte edilmiştir. Kamera çubuğa monte edilmeden önce kumandalı çekim için gerekli ayarlar yapılıp, uzaktan kumanda araçları kameraya takılmıştır. Bir kişi çubuğu sabit tutarken diğer bir kişi de çubuğu tutan kişiyi yönlendirerek kameranın mümkün olduğu kadar yüzeye paralel olmasını sağlamış ve uzaktan kumanda ile çekimleri gerçekleştirmiştir. Bu şekilde kuşbakışı çekimler tamamlandıktan sonra ilgili alanın detaylı şekilde yerden de fotoğrafları çekilmiştir. Fotoğraf çekimine başlanmadan önce yerleştirilen fotogrametrik kontrol noktaları Geomax Zoom 30 marka total station ile ölçülmüştür. Bu noktalar hem modelin coğrafi konumlandırılması için hem de doğruluk analizi için kullanılmıştır.

Çalışma giriş, metrik ölçme yöntemleri, örnek çalışma, sonuç ve öneriler olmak üzere dört ana başlıkta toplanmıştır.

İlk bölümde çalışma hakkında kısaca bilgi verildikten sonra çalışmanın amacı ve kapsamı tanımlanmıştır. Kültürel miras kavramına açıklık getirilerek neden korunması gerektiği tartışılmış, kültürel mirasa ülkemizdeki bakış açısına örnek teşkil eden yakın tarihimiz incelenerek güncel haberlerden bir kaç örnek verilmiştir. Daha sonra korumada belgelemenin önemine değinerek hangi detay ve doğrulukta nasıl bir belgeleme çalışması yapılabileceği tablolar ile özetlenmiştir.

İkinci bölümde metrik ölçme yöntemleri ele alınarak geleneksel yöntemler, topografik yöntem, lazer tarama yöntemi ve fotogrametrik yöntemler şekiller verilerek kapsamlıca açıklanmıştır.

Üçüncü bölümde örnek çalışma alanı olarak seçilen Sagalassos Antik Kenti ve 1995'ten bu yana devam eden kazı çalışmaları hakkında bilgiler verilmiştir. Uygulanmak için seçilen fotogrametrik yöntem detaylıca açıklanarak seçilen açmada nasıl kullanıldığı adım adım anlatılmıştır. Elde edilen foto-gerçekçi modelin doğruluk analizi total station ile ölçülen kontrol noktalarının koordinatları ile modeldeki konumlarının koordinatlarının farkı alınmasıyla yapılmıştır. Bütün değerler bir tabloda toplanarak farklar gösterilmiş ve ortalama hata miktarı hesaplanmıştır. Ayrıca hata vektörlerinin büyüklüklerini ve yönlerini gösteren, çalışmanın hangi detayda yapılabileceğine örnek teşkil edecek modelden alınmış kuşabakışı bir orto-imaj yaratılmıştır.

Son bölümde ise elde edilen sonuçlar göz önüne alınarak çalışmanın belgeleme için uygun olup olmayacağı tartışılmıştır. Gelecekte yapılabilecek bazı çalışmalar örneklenmiştir: Elde edilen üç boyutlu model, düzenleme yazılımlarına kolayca aktarılarak üç boyutlu anastilosis, rekonstrüksiyon ve restorasyon projeleri gerçekleştirilebilir. İnsansız hava araçları kullanılarak geniş alanların modelleri, orto-imajları veya yükseklik modelleri üretilebilir. Açmalardaki kazı süresince ortaya çıkan bütün tabakalar modellenerek bütün bir kazı süreci üç boyutlu analiz edilebilir.

Bu çalışmada özellikle kazı döneminin sonunda açmaların içindeki hassas mimari kalıntıların belgelenmesine odaklanılmıştır. Ele alınan metod ve elde edilen sonuçlar diğer yaygın kullanılan üç boyutlu sistemler ile kıyaslanmış ve çalışmanın sonunda sunulmuştur. Bu yöntemin geleneksel yöntemin yerine kullanılabilirliği ayrıca tartışılmış, sonuçlar metodun metrik belgeleme için yeterince hızlı ve doğru bir metod olduğunu ortaya koymuştur.

1. INTRODUCTION

Anatolia, which occupies the greater part of the Republic of Turkey, has a rich history of inhabitance and is therefore considered as an archaeologically 'rich' area [1]. It has been found that 42 different civilizations lived in Anatolia before the Ottoman period [2]. Such a richness does not only belong to Republic of Turkey nor the actual generation, it belongs to the entire humanity. Although this heritage should be transferred to the next generations, it is exposed to destruction by mankind, due to inadequate maintenance, lack of financial and/or human resources, state development projects and armed conflict. It is a sad fact that everything cannot be protected, but it may be documented before it is lost.

Documentation is a crucial process for conservation and preservation. It has to be considered as one of the first steps before any conservation actions. Metric recording is an important part of the documentation process. There are several recording techniques and this study focuses on one of them: photogrammetry.

"Photogrammetry is the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images" [3]. In other words, photogrammetry is the ability to capture measurements directly from photographs or products derived by using photographs. Especially digital photogrammetry enables to create three-dimensional information rapidly and accurately, using multiple overlapped photographs of a relevant area or subject.

Photogrammetric methods are generally used for two-dimensional documentation and measuring purposes, for instance to produce elevation drawings of facades from rectified photographs. However, digital photogrammetry makes it also possible to produce 3D point clouds and models of relevant areas using structure from motion (SfM) and multi-view stereo (MVS) algorithms. Parallel to the improvements in related computer technology, digital photogrammetry is expected to improve greatly in terms of speed and accuracy. Taking into account the user friendly and significantly low cost with regard to other 3D techniques, this method is very promising to be highly preferable for 3D recording purposes. Due to these reasons, photogrammetric methods became an alternative for the recording of cultural heritage, especially for archaeological excavations in recent years.

1.1 Research Aim

Accurate metric recording has always been a crucial scientific component of archaeology. Conventional 2D recording techniques in the form of orthographic drawings and/or photography are being increasingly challenged in the last decade by the 3D methods that offer user friendly, low cost and time efficient solutions. This study presents an image based 3D registration technique employed in 2013 at the ancient city of Sagalassos, using structure from motion and multi-view stereo algorithms. It specifically focusses on the documentation of exposed fragile architectural remains in a trench, at the end of the excavations. A digital camera is used to take photographs, a total station is used to measure control points which are necessary for geo-referencing and analysing the accuracy of the method, and a commercial software is used to be able to produce a 3D model of a trench using relevant photographs.

This thesis consists of 4 sections. In the first section, it tries to find an answer to questions like; what is heritage, why is it necessary to document it, what is the importance of metric recording, what are the necessary tools for heritage recording, and what is the purpose of this study. The second section of this research demonstrates the metric recording techniques. The third section consists of information about the ancient city of Sagalassos, the methodology applied for the metric recording in the 2013 campaign in Sagalassos, the field and office works which were necessary to produce the metric record of a trench, and the results of the image based product. The last section investigates if the results are efficient for the chosen purpose, and what the future of this technique can be.

1.2 Heritage

The terminology of heritage is dynamic since practices and philosophies of heritage are constantly evolving. Therefore the search for better ways of understanding and preserving heritage is a never ending process. [4]

"If we want to preserve something, then it is our heritage". This is how François le Blanc, a specialist in heritage conservation, defines heritage. On the other hand preservation of heritage has become an irrepressible problem. When we consider the recent past of Turkey, it can be said that it is getting a bigger issue day by day. After the Second World War, the governments of the Republic of Turkey have chosen to have liberal based economies. During the Prime Minister Menderes period (1950-1960) Marshall Foundations, uncontrolled urbanization, and state development projects caused devastation of archaeological and historical settlements. The year 1980 can be considered as a breakthrough in recent history of Turkey; Turkey met with a new economic system so called neo-liberalism. Turkish economy started to be an active player in global capitalism; to become a world market, to develop industrialism aimed at exportation, and to attract foreign and domestic investors were some of the goals of 24th of January decisions [5]. Preservation of cultural heritage became even more difficult with the neo-liberal economy, which became unstoppable since the 2000s.

Rapid industrial progress changed the needs and priorities of authorities. Today, governments choose to spare budget mostly for profit-oriented investments. Hence the cultural heritage sites which are mostly non-profit scientific research projects, are often left to destruction instead of being protected. According to the TAY (Archaeological Settlements of Turkey) Project; agriculture, contemporary settlements, illicit digging/treasure hunting, highways, roads, bridges etc., natural causes and mines/quarries are some of the main reasons that cause the destruction of cultural heritage sites (Figure 1.1, Figure 1.2) [6].

A successful preservation and protection plan requires to have a clear and detailed documentation process. Documentation should analyse in what condition the heritage sites and settlements exist, likewise it should evaluate the causes of degradation and destruction. In the summer of 2000, the TAY Project started a sub-project called TAYEx (TAY Expedition) to achieve the documentation of the current condition as well as the level of destruction of all sites and settlements such as mounds, caves, rock shelters, flat settlements, tumuli, and cemeteries. The statistic of the regional destruction is outlined below:

- Marmara Region: The number of total settlements is 202. 160 of them are subject to destruction. 36 Sites are in a state of emergency and 17 of them are severely damaged and/or vanished.
- Aegean Region: The number of total settlements is 204. 139 of them are subject to destruction. 48 Sites are in a state of emergency and 23 of them are severely damaged and/or vanished.
- Mediterranean Region: The number of total settlements is 456. 341 of them are subject to destruction. 109 Sites are in a state of emergency and 62 of them are severely damaged and/or vanished.
- South-eastern Anatolia Region: The number of total settlements is 338. 174 of them are subject to destruction. 36 Sites are in a state of emergency and 23 of them are severely damaged and/or vanished. Apart from this destroyed sites, the dams have destroyed 64 settlements.
- Central Anatolia Region: The number of total settlements is 627. 439 of them are subject to destruction. 137 Sites are in a state of emergency and 87 of them are severely damaged and/or vanished.
- Black Sea - Eastern Anatolia Region: The number of total settlements is 766. 589 of them are subject to destruction. 193 Sites are in a state of emergency and 86 of them are severely damaged and/or vanished.

This report shows the level of destruction and the importance of documentation.

Figure 1.1 : Left: *"Cultural and Natural Heritage Preservation Board reach a verdict to not preserve Allianoi"* the ancient city of Allinoi was stuffed with sand and left under the water when Yortanlı Dam closed its floodgate in 31st of December, 2010 [7].

Right: *"TOKİ houses in Bathonea Ancient City!"* TOKİ consulted the Cultural and Natural Heritage Preservation Board to have a permission to build houses in an archaeological site in March, 2014 [8].

Figure 1.2 : Left: *"2700 years old ancient city is zoned for construction"* Myrelina Ancient City is announced as finance and truism zone in the master development plan which was prepared by Bursa Metropolitan Municipality [9].

Right: *"5 stars crazy project in the ancient cit*y" The owner of the Rixxos Otels starts a new otel project in National Park of Beydağları Olimpos. The land of the project contains a part of a first degree archaeological site. Phasalis Ancient City lies in this area [10].

1.3 Documentation and Recording of Cultural Heritage

Architectural and archaeological cultural heritage is being lost because of human caused harm, such as war and uncontrolled development, or natural disasters, neglect, and inappropriate conservation. Although it is requisite to preserve as much as possible of our architectural and archaeological cultural heritage, it is a fact that everything cannot be saved. Therefore heritage should be documented before it is lost.

Documentation is stock of information which collects information systematically and archives the records for future reference. It is a general saying that today's recording is tomorrow's documentation. Documentation consists of records produced by professionals and people from different fields of expertise and interest [11].

Every research or conservation activity starts with an investigation of heritage records, and therefore heritage records should be easy accessible and reliable. The records should have accurate information about the identity, location and setting of the heritage, and mention sources where related information can be found. The records should also contain metric, quantitative, and qualitative data from the viewpoint of multiple dicsiplines. [11]

Getty Institute considered recording in three levels: reconnaissance recording, preliminary recording and detailed recording. Reconnaissance recording consists of quick sketches and photographs which give an impression of the heritage site and its configuration at the start of a project. Preliminary recording adds more specific information to the project dossier to ensure a good understanding of the projects requirements in the beginning of the process. Detailed recording provides graphic records which serve as accurate outlines for detailed studies (Table 1.1). [11]

The decision of which metric recording tools will be used also depends on factors like budget, time, equipment and specialized technicians, and how accurate and detailed the results should be. Traditional recording techniques are still effective for recording. A successful recording process can be achieved by using these techniques with small budgets and well trained recorders who have to be familiar with the heritage place. Accuracy and verification, time, and limited visualization can be listed as the disadvantages of the traditional techniques. The recent computer technology forces the traditional recording techniques to change into digital heritage recording. This technology can be represented as producing and storing any digital information such as; measured drawings, photographs, photogrammetric products, and other electronic data. The recording activity might be completed using a single tool as well as it can be necessary to combine the required recording tools like, using a Tablet PC combined with low cost photograph rectification software. The method which can be used according the chosen accuracy (low, medium or high) is listed in the table 1.2. [11]

Table 1.1 : The three levels of heritage recording. The choice of different levels depends on the project needs in terms of accuracy and detail, arising at different stages of the conservation process.

Levels of Heritage Recording	A Reconnaissance Record Low Accuracy	B Preliminary Record Midrange Accuracy	C Detailed Record High Accuracy
Purpose of Recording	Reconnaissance Initial inventory Initial planning Reference data	Planning Initial condition Investigation Stabilization Pre-design Reference data	As-found condition Design Construction As-built record Maintenance/monitoring Posterity
Accuracy of Drawings	Not to scale	Plans and elevations ± 5.0 in. (± 10 cm) Details ± 1.0 in. (± 2 cm)	Plans and elevations ± 0.5 in. (± 1 cm) Details ± 0.1 in. (± 2 mm)
Results	Photographic report Photo-key plan Initial condition Descriptive sketches	Measured drawings Asset description/condition Observations Photographic report	Measured drawings Asset description/condition Observations Photographic report
Cost (will vary in absolute terms with scale and complexity of site)	Low (a few days on site by recording team)	Moderate (several weeks or more on site by heritage recording team and input by conservation professionals)	Moderate to high (extensive and possibly ongoing activity on site by recording team and increased input by conservation professionals)

Table 1.2 : Recommended framework for development and use of recording tools.

Heritage Recording Tools	A Low Accuracy	B Midrange Accuracy	C High Accuracy
Traditional Recording Tools			
	35mm photography* Sketches	Hand recording Large-format photography* Small-format rectified photography*	Hand recording Large-format rectified photography* Stereophotogrammetry*
Digital Recording Tools			
Vector Records (CAD)	CAD measured drawing GPS	CAD measured drawing CAD overlaying rectified photos GPS 3-D modeling	Digital photogrammetry Total station GPS 3-D modeling 3-D laser scanning
Raster Records (Imaging)	Digital photography Scanning of photographs Digital video Tablet PC	Digital photo rectification High-resolution digital video Tablet PC	Texture mapping of 3-D models Orthophotography Tablet PC

*Note: Film is becoming scarce, and digital photography is cost effective and constantly improving.

2. METRIC RECORDING TECHNIQUES

Metric recording is to capture, by using graphic or photographic methods, spatial information describing the position and the actual existing form, shape and size of heritage at known points in time [11, 12, 13]. There are four metric recording techniques: conventional, tacheometric, laser scanner, and photogrammetric.

2.1 Conventional Techniques

There are two main stages in conventional techniques: sketching and measuring. In the sketching process, buildings or objects are visually expressed by a manual drawing to a graph paper. Photographical survey may also be a very useful tool for understanding the structure if some parts are missing in the sketch. The drawings of the structure mostly consist of orthogonal views in a required scale and for each view there has to be a sketch of the relevant scene. But it can sometimes be necessary to plot axonometric projections to understand the three dimensions of the structure better when the orthogonal sketches or photographic survey are not sufficient. The measuring process is performed by direct measuring tools such as tape or a laser distance meter, a plumb line, range rod and levelling rod. The measuring process can sometimes be dangerous or even impractical while measuring the high parts, especially if the building is damaged. [12, 14]

2.1.1 Directly Plotted Drawings

Drawings made by plotting to scale on site are also known as direct plots, and are usually used for 1:20 and 1:10 scale drawings of building elevations, trench profiles in archaeological investigations and to plot underwater archaeological remains as well. A grid which is placed over the subject, is used as a reference frame to measure the relevant area and transfer these measurements into a hard copy at scale (Figure 2.1) [12]. Afterwards the hard copy can be scanned and digitized in a CAD environment and eventually both, soft and hard, formats should be archived.

A planning frame should be used to plot the remains exposed by excavation in an archaeological site. These remains need to be removed to be able to continue the excavation. Therefore there won't be a second chance to plot the information revealed. For that reason, the drawings must follow systematic and reliable steps. Planning frames must be levelled before any plotting action and need to be attached with a common co-ordinate system to make it possible to record every frame according to each other. The planning frame can be flipped to record profile or elevation details. [12]

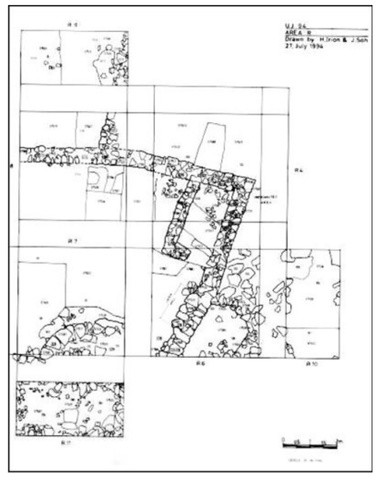

Figure 2.1 : Left: Recording a wall using directly plotted measuring method with the help of a rigid recording frame. Right: Direct plot of a part of an excavation plan onto gridded drafting film at 1:20 scale.

2.1.2 Measured drawings

Measured drawings, also known as dimensioned sketches, are based on a clear, understandable and scaled sketching process which depends directly on the draughtsman's experience and expertise. Annotating the related measurements to the sketch is the second step [12]. Measurements are taken with basic measurement tools such as tape or a laser distance meter, plumb line, range rod and levelling rod [14]. The triangulation method is a very important factor of the measurement process aspects of accuracy and control of the measurements. After establishing the reference lines and points, which are crucial in this method, any detail can be measured based on the triangulation between reference lines or points and details subject to be measured. These reference lines can consist of two perpendicular lines as x and y axis or a rectangular reference box (Figure 2.2) [15]. Only one base line can also be used if the object's size is relatively smaller, like in case of individual parts of a structure.

On the one hand, a detailed sketching process helps to improve the surveyor's knowledge of the structure. On the other hand this technique is directly dependant on the measured drawing practitioners wherefore it triggers the risk of wrong measurements which may imperil the final drawings. This can cause irrevocable mistakes, especially if there is no chance to visit the site again, yet photographic survey may help to overcome this problem. [12]

The structure should be represented in orthographic drawings as elevations, sections and plans. Sometimes, axonometric drawings may be helpful to understand the three dimensions of the structure. The elevations surveyed by hand and the sections and plans shall be kept as a document and the manual drawings must be re-drawn in a CAD environment. [12, 14]

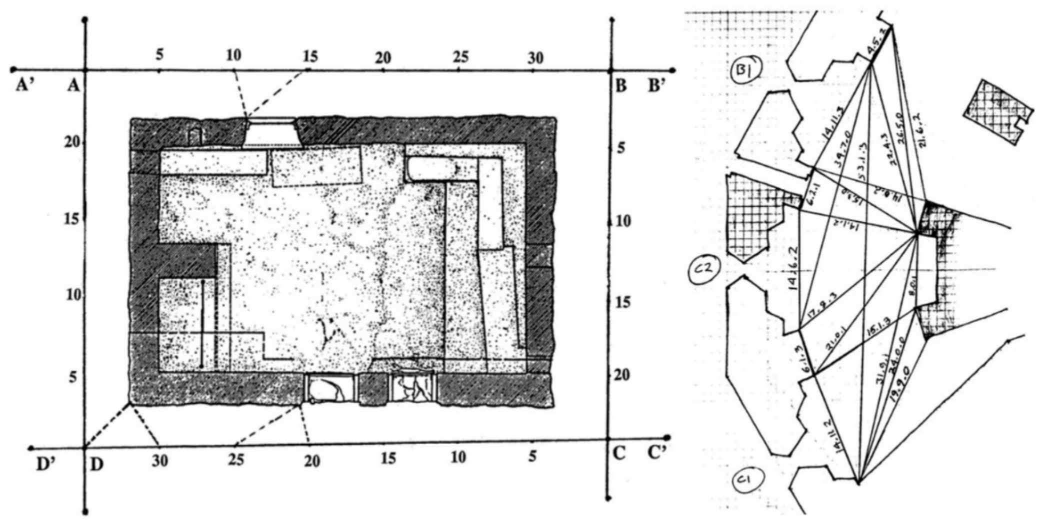

Figure 2.2 : Examples of using rectangular box and triangulation method.

2.2 Tacheometric Technique

This method has basically the same principle and steps as the measured drawings technique; sketching and measuring. The only difference between these techniques is the measuring process. Instead of using direct measurement tools, a total station instrument is used to measure the required points that help to produce orthogonal (and axonometric if necessary) drawings. The total station is an electronic theodolite (transit) integrated with an electronic distance meter (EDM) and microprocessor. This way, the instrument reads slope distances from the instrument to a particular point with

EDM, calculates the X,Y,Z coordinates of the points with a microprocessor, and stores them in digital form [16].

Before the measuring process, the subject area should be sketched onto a milimetric paper, with a determined scale as much as possible. The sketch should contain the name of the draughtsman, the estimated north and the date of measuring, to avoid any misunderstanding. After sketching, the draughtsman has to annotate the numbers of the points to the sketch simultaneously with the measuring process (Figure 2.3). Wrong numbering or missing measuring can cause unrecoverable mistakes. Therefore, the draughtsman and surveyor should communicate with each other when necessary. After the sketching and measuring process, the measured points can be imported directly to a CAD environment, and the drawing process can be performed digitally, using measured points and sketches (Figure 2.4).

Figure 2.3 : Sketching and measuring with tacheometrical technique.

The results are presented either as 2D elevations or 3D models in a CAD environment [14]. A reflectorless measurement tool enables to measure facades and unreachable or dangerous places. Not only does this method make it easier to link the measurements to a local or global coordinate frame but it is faster and more accurate than the conventional technique as well.

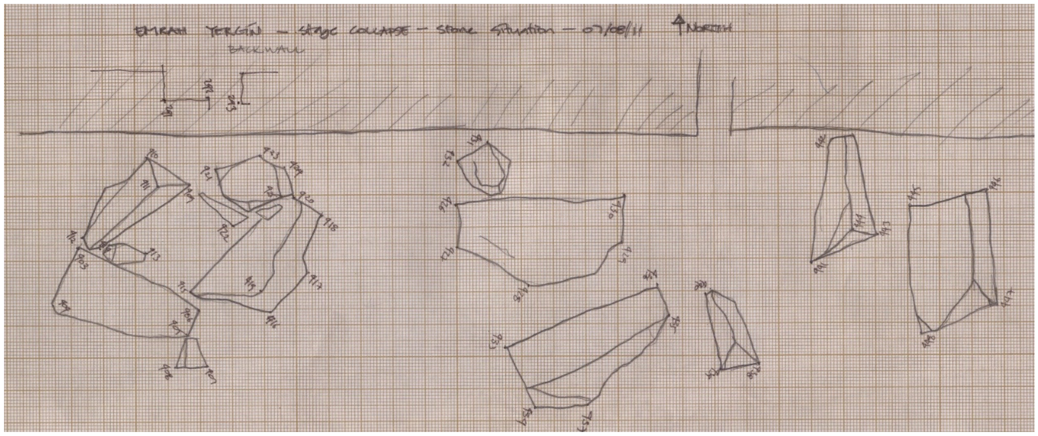

Figure 2.4 : An example of a sketch.

2.3 Terrestrial Laser Scanning Technique

Terrestrial laser scanning can be described as a highly automated reflectorless total station, which measures automatically hundreds of thousands points in its horizantal and vertical field in seconds, relatively to the position of the scanner [44] (Figure 2.5). Terrestrial laser scanners can collect 3D data according to the principle of phase-shift or time of flight. “The phase-shift principle compares the phase of the laser source with the same when the radiation comes back again to the scanner after its reflection on object’s surface. This type of tls emit continuously a periodical signal of moderate intensity” [45]. In the time of flight principible, a short laser pulse is sent to the object and is reflected on its surface; in this way the reflected radiation returns to the scanner and is there detected by a sensor. When the light-speed is known and the time elapsed between the emission and reception of the pulse can be calculated, the range to thse object can be determined by half of the round-trip distance. [45]

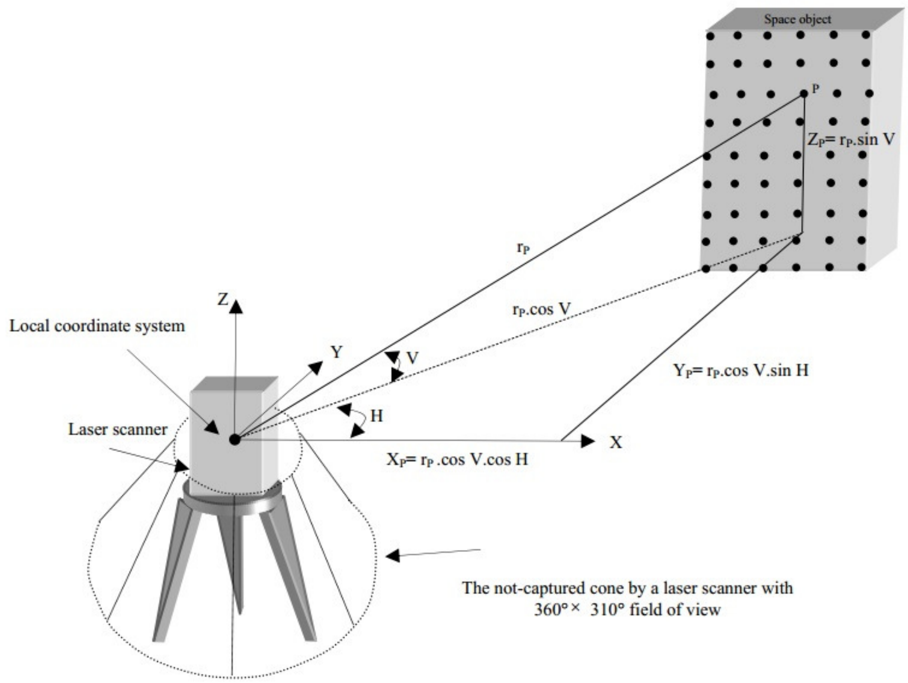

Figure 2.5 : Three-dimensional measuring using laser scanner.

The terrestrial Laser Scanning Technique (TLS) is a very accurate and fast method to document any kind of site or object, cultural or commercial [17,18]. However, TLS instruments are too expensive to purchase for archaeological excavations due to their limited budgets. Thus, the TLS is commonly used for specific projects, mostly large structures such as ancient theatres, within the context of time efficiency (Figure 2.6). Moreover, to use this method, technically trained personnel is required to collect and process obtained 3D data. The ancient theatres of Dionysus [19] and Nea Paphos [20] in Greece, Ephesus in Turkey [21, 22], Taormina, the tower of Pisa [23] and the Forum of Pompeii [24] in Italy etc. are some large scale monuments subjected to 3D documentation using TLS.

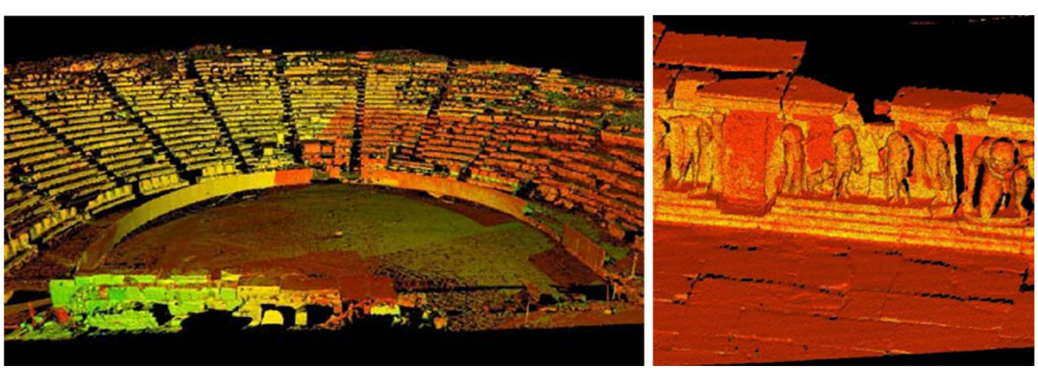

Figure 2.6 : 3D mesh of the ancient theatre of Dionysus created by TLS technique.

2.4 Photogrammetric Techniques

Another alternative for fast 3D recording is the use of photogrammetric methods. Photogrammetry is applied mostly with the intention of 2D measuring and documentation such as elavation drawings of facades [14]. However, digital photogrammetry makes it possible to produce 3D point clouds and eventually 3D models of relevant areas using structure from motion (SfM) and multi-view stereo (MVS) algorithms, which are basically based on overlapped images.

Photogrammetric methods enable measurement, interpretation and analysis of features and scenes directly from images or photogrammetric products [46].

The improvement of photogrammetry undoubtedly depends on the general development of technology; the four major phases of photogrammetry (Figure 2.7) are directly related to the technological inventions of photography, airplanes, computers and electronics [47].

During the past three decades digital technologies have lead to invention and effective usage of powerful desktop computers and sophisticated viewing softwares. This progress has resulted in the increased popularity of digital photogrammetry, which uses digital rather than analogue images. Even more recently, digital close-range photography taken at both vertical and oblique angles became very popular as a conclusion. Softcopy photogrammetry enables faster, easier, and a more simple modus operandi, and costs less than analogue analytical methods. It is also more flexible than earlier methods: it automates many time consuming and complex functions, which makes it an optimal tool for photogrammetrists. [46]

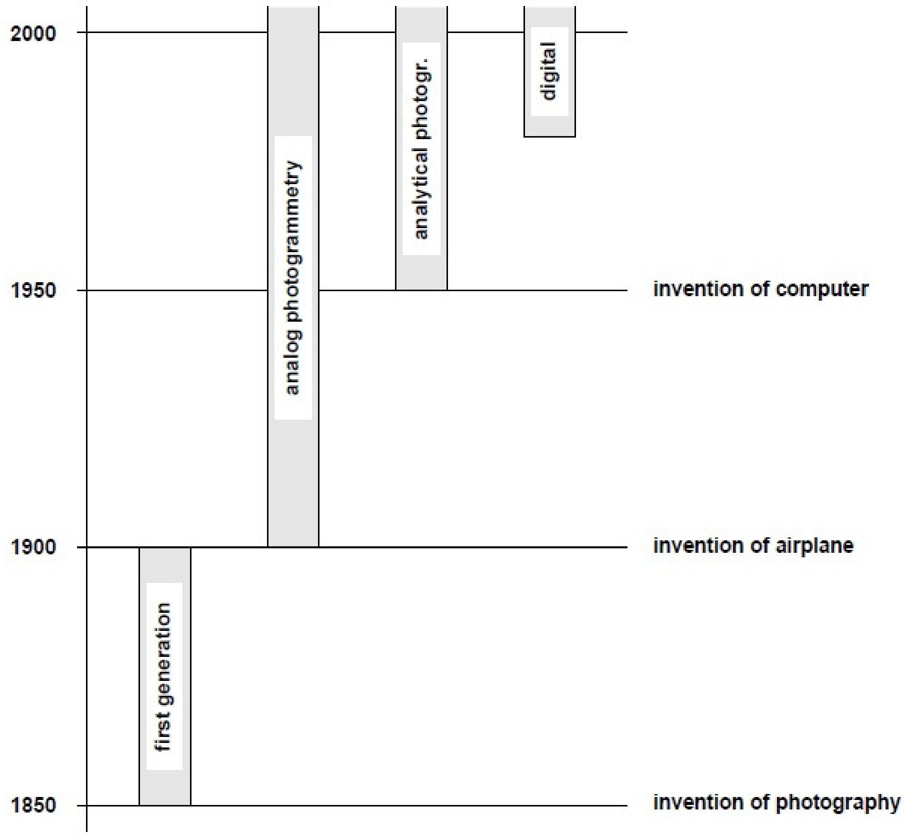

Figure 2.7 : The development of photogrammetry related with technological inventions.

This thesis will focus on the last phase of photogrammetry which is called digital or softcopy photogrammetry within the context of documentation of cultural heritage. Since the late 1990's and early 2000's there have been several large archaeological projects employing the method for documentation purposes [48]. The photogrammetric techniques are investigated in two sections; two-dimensional rectification techniques and three-dimensional techniques.

2.4.1 Two-dimensional rectification techniques

Rectification is the process of making equivalent vertical photographs from tilted photographs (Figure 2.8) [3]. Although rectified photographs are theoretically true vertical photographs, they still contain relief displacements and scale variations which can be removed in a process called differential rectification or orthorectification. The resulting products are then called ortho-photos [14].

The workflow of two-dimensional rectification consists of three steps: control points placement and measurement, image capture, and image processing. At least three ground control points, measured by a totalstation or GPS, must be visible in each image for the rectification process. In the second step, the images should be taken from the most perpendicular angle to the surface, because oblique images cause low accuracy. And the last step can be performed by various softwares, commercial or non-commercial, with different approaches.

Figure 2.8 : Original and rectified (in scale) photographs of a façade.

Single-image rectification is commonly applied by archaeologists and architects to obtain fairly accurate and useful two-dimensional measurements (Figure 2.9). Besides that, two-dimensional images can be helpful to analyse temporal change (by registering two images taken at different times), and mosaicing [46]. However, a very large amount of three-dimensional data can't be used following this method [46]. Robert Daniels, an archaeologist, drew attention to this matter: "traditional methods are insufficient for efficient and accurate recording, storing, and relating the evidence that is quantitatively large, architecturally complex, and three-dimensional in nature" [48]

Figure 2.9 : Photogrammetric documentation of Necatibey Boulevard using rectified images.

2.4.2 Three-dimensional techniques

Recent progress in computer science allows to record three-dimensional data of a feature using two or more overlapped digital photographs with inexpensive photogrammetric tools. Within the context of documentation, stereo photogrammetry techniques, and more recently multistation monoscopic photogrammetry techniques are applied.

2.4.2.1 Stereo photogrammetry techniques

Stereo close-range photogrammetry is an approach that is capable of recording almost any object. Using "stereo pairs of images" arbitrary shapes of 3D geometry can be reconstructed as long as the area of interest is shown on both images with the 60% minumum overlap ratio (Figure 2.10). The camera directions should be as much as parallel to each other to have a good stereoscopic viewing [49]. Before the image processing, it is recommended to calibrate the digital cameras to minimize distortion issues such as radial distortion common in low-end cameras. There are several commercial and free tools in use for camera calibration. For archeaological excavations, it is useful to build a scaffolding over the subject area to be photographed (Figure 2.11). This method allows to take photographs from a certain height, with an angle as close to perpendicular as possible. Ground control points should cover the related area as at least three of them fall to each frame. Measurement of the ground control points can be performed by a total station, preferably a reflectorless one, before or after the image capturing process. Measuring the dimensions of the feature and some distances between the control points helps in later rectification, error analysis, and blunder checking. [46]

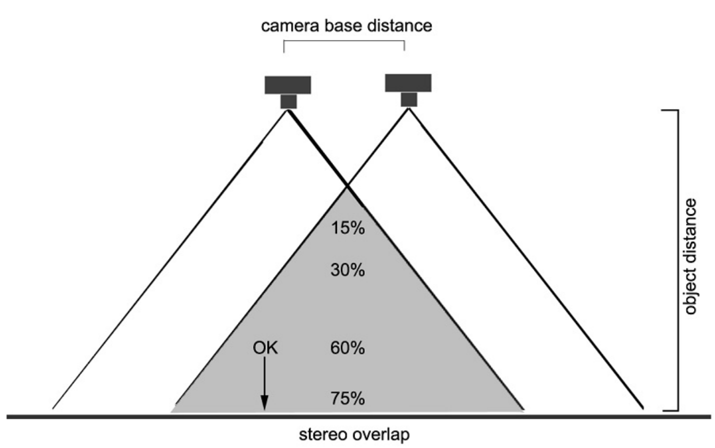

Figure 2.10 : The camera base/object distance concept.

Results of stereographic restitution can be: two-dimensional plans of single facades, three-dimensional wireframe and surface models [49].

Figure 2.11 : Image capture for stereo photogrammetric techniques with the help of a scaffholding.

2.4.2.2 Multistation monoscopic photogrammetry techniques

In many cases the use of one single stereo pair will not suffice to reconstruct a complex structure. Therefore it is necessary to use more images from different angles and positions to cover the subject area as a whole (Figure 2.12) [49]. Recent technological developments enable to build 3D reconstructions of relevant subjects or areas in almost any size. Multistation monoscopic photogrammetry techniques can be reviewed in two sections: semi-manual or automated extraction of 3D point data. In the case study of this thesis, performed in an excavation site of the ancient city of Sagalassos, an automated approach using a commercial software is applied. Therefore this matter will be discussed detailedly in the methodology section of this thesis.

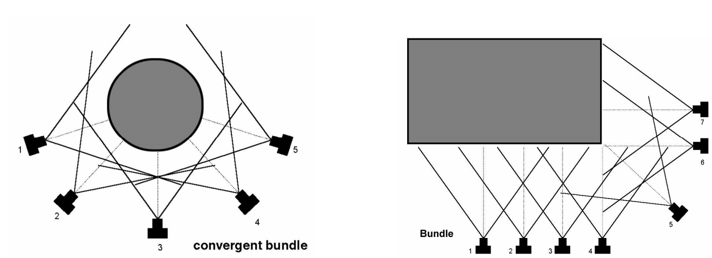

Figure 2.12 : The image acquisition process for multistation monoscopic method.

Multistation monoscopic photogrammetry became a point of interest in the 1990s, after a well known photogrammetric software named PhotoModeler was released. PhotoModeler is used in archaeology, historic preservation, biology, engineering, and forensics [46]. The software uses digital imagery to produce 3D photo-realistic models, with the manual extraction of 3D points, lines and splines (Figure 2.13). The workflow of this method is similar with the other photogrammetric methods: fieldwork and image processing steps. Firstly the relevent area should be covered with ground control points which are coordinated by a totalstation. These points are necessary to determine the interior and exterior orientation of the cameras, and for the adjustment process as well. Then the subject area should be photographed from different angles and positions while the images overlap around 60 percent. And in the last step, the images should be processed with a suitable software package.

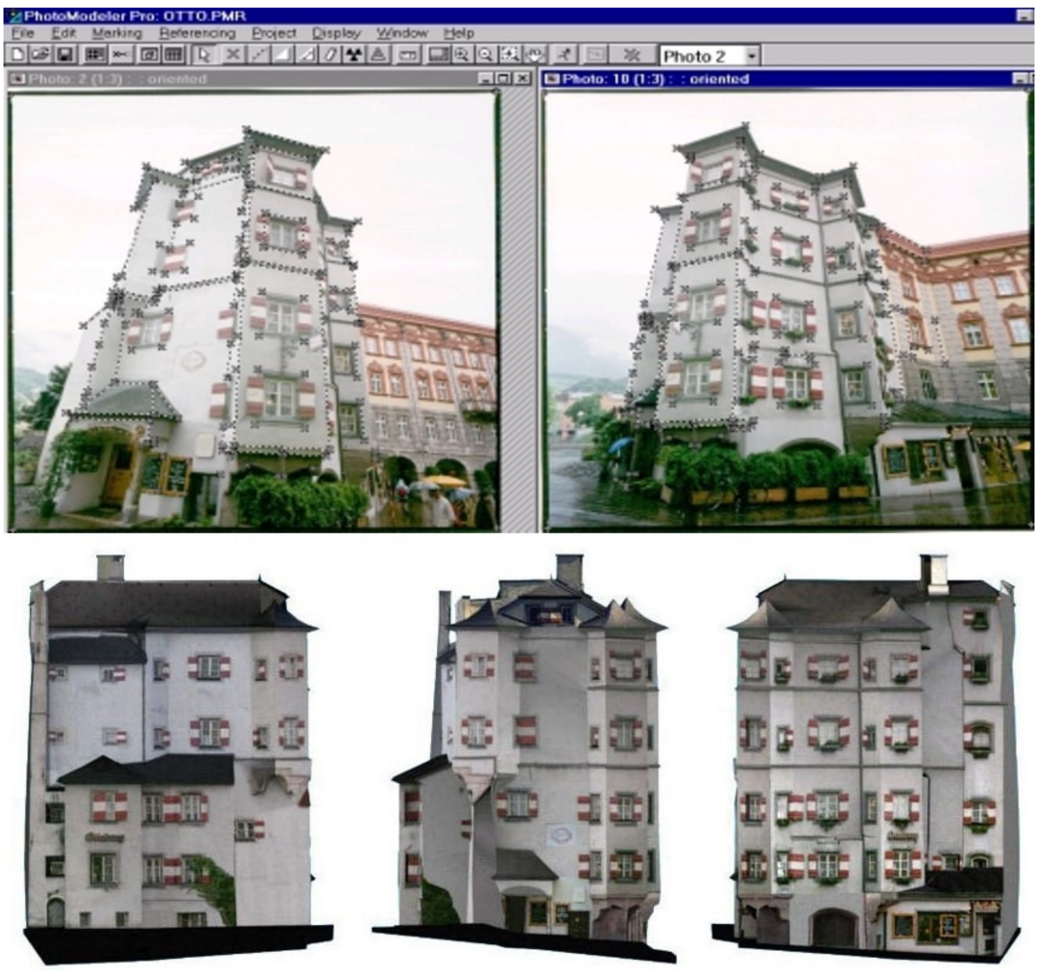

Figure 2.13 : 3D measurements using PhotoModeler software and ortho-images of facedes from created 3D model of Ottoburg building in Innsbruck.

The results of this method can be exported in a variety of different formats to be used in different environments: 3D wireframe and surface models of the objects, digital elevation models, coloured dense or sparse point clouds, coloured mesh formats and true ortho-images.

Parallel to the improvements in related computer technology, digital photogrammetry is expected to improve greatly in terms of speed and accuracy. Taking into account the user friendly and significantly low cost with regard to other techniques, this method is very promising to be highly preferable for 3D documentation purposes.

Table 2.1 : Summary of metric methods for heritage documentation.

		PRODUCT	CAN BE USED FOR	TYPICAL OUTPUT SCALE	TYPICAL RANGE	REQUIRES THE USE OF
INDIRECT:						
PHOTOGRAMMETRY	2D	Satellite imagery	remote sensing	1:5000		post-processing and 3D modelling software + specialist 3D CAD /GIS skills
	3D	Stereo pairs	Condition recording and ante- disaster records.			Calibrated camera, precise control data
		Wire-frame CAD drawings	'Stone by stone' drawings, landscape survey, condition recording, works scheduling	1:20 – 1:200	5 -50m	
	2D	Orthophotographs				Photogrammetric plotting system – experienced operator + image interpretation skills, Image processing, CAD and 3D modelling software + CAD skills
	3D	Digital Elevation Models (DEM)	Condition monitoring, modelling and reverse engineering, visualisations	1:5 – 1:50		
LASER SCANNING						
AIRBORNE LIDAR	3D	Point clouds	Prospecting landforms	1:50 - 1:100	5-200m	Scanner, post-processing and 3D modelling software reverse engineering software + specialist 3D CAD skills
TERRESTRIAL SCANNER			3D Surface modelling			
ARTEFACT SCANNER			Replica components and castings	actual size – 1:10	0.5-2m	
RECTIFIED PHOTOGRAPHY	2D	Scaled images	Condition recording and assessments, works scheduling	1:20 – 1:50	5 - 50m	Metric or non-metric camera, precise control data or scaling information, rectification software
DIRECT:						
DRAWING		Sketches	Diagnostics, support to 3D modelling		0-30m	Trained draughts-person + CAD skills
	2D	Measured Drawings	Plans, sections etc	1:20-1:50		
LEVELLING		Precise levelling	Monitoring structures	1:20-1:50	1-30m	Trained survey personnel +monitoring regime
EDM		Point data	Terrain models			EDM set + field CAD unit +CAD skills
	3D	Wire-frame CAD drawings	Plans, sections etc	1:50	5-100m	
		Control data	Monitoring and metric data integration	1:20 - 1:500		EDM set + specialist survey skills
GPS		Point data	Terrain models			
	3D	Wire-frame CAD drawings	Control data, Site plans, landscape survey	1:100	20-500m	GPS set + specialist survey skills

3. CASE STUDY

3.1 History of The Ancient City of Sagalassos

Sagalassos is located in south-west Turkey, north of Antalya (the 5th biggest city of Turkey), near the present town of Ağlasun in Burdur, in the antique region of Pisidia, now known as the “Lake Region” (Figure 3.1). The town was settled at altitudes between 1450 and 1600 m. The 1800 m high Akdağ is located on the north of Sagalassos. South of the city, around the modern town of Ağlasun there is a lush, green plain. The region has a climate with short, hot, mainly dry summers and colder, wetter winters compared to coastal regions close to Sagalassos, due to its position and mountainous character. The first traces of hunter/gatherers in the territory are found 12000 years before present. The mountain site of Salawassa, which was possibly identified as Sagalassos later, was mentioned in Hittite documents in 14th century BC. In the course of the Persian period, Pisidia became known for its aggressive and rebellious factions. In 333 BC, the city was invaded by Alexander the Great due to its strategic position. [50]

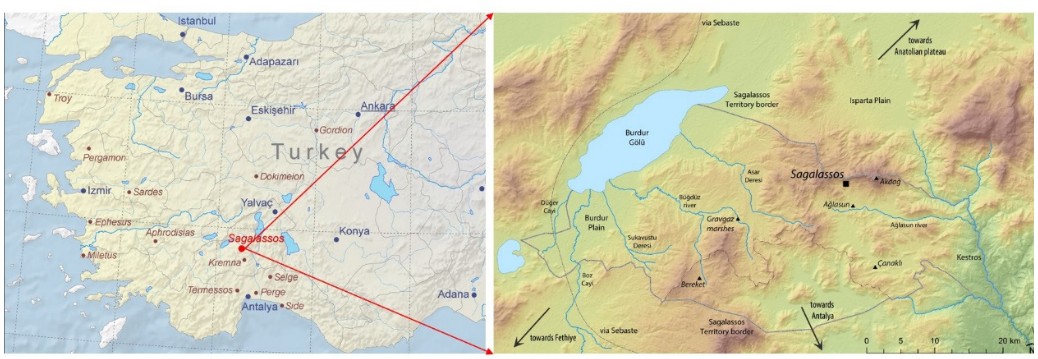

Figure 3.1 : Location of the Ancient City of Sagalassos.

Pisidia changed hands many times; the region was integrated into the kingdom of Antigonos Monopthalmos between 321-301 BC, perhaps Lysimachos of Thrace controlled the region between 301-281 BC, the Seleucids of Syria between 281-189 BC, and the Attalids of Pergamon between 189-133 BC. After Rome took over the

Attalids' kingdom, Pisidia became a part of the different Roman provinces of Asia and in 25 BC, Rome created the province of Galatia. Under Roman Imperial rule, Sagalassos initiated to export local industrial products, and in a short time the city became the metropolis of Pisidia [50].

Around 400 AD, the town had been attacked by Isaurians, and it had received a serious blow by an earthquake in 518 AD. Nevertheless, the city had overcome and was restored again. During the 5th century, Sagalassos became the second most important bishopric of Pisidia under the domination of Christianity. [52]

The eventual decline had started with the plague of AD 541-542, which resulted in loss of half of the population. The last inhabitants finally abandoned the civic centre around the middle of the 7th century AD, after another major earthquake, new epidemics and the first Arab raids [51]. As a result, a massive erosion covered (and secured) the ruins of the abandoned city. Therefore Sagalassos has a great potential for archaeological research programmes. [52]

Since 1990 KU Leuven carries out an interdisciplinary research project in the 1200 km^2 territory of Sagalassos, concentrated specifically at the centre and the eastern suburbia, where they revealed a great deal of the fabric of the ancient city. The excavations cause the archaeological remains (city structures, mosaic floors, ashlar and rubble stone and/or brick masonry structures) to be exposed to severe weathering conditions. The fragile remains located on a high altitude require suitable documentation, conservation and management techniques. [25, 26]

The presented case study discusses the 3D capture of the exposed remains at one of the excavated areas within the Sagalassos city centre during the 2013 campaign, namely the trenches located on the east of the Neon Library, where is code named 'LE' trenches (Figure 3.2). The purpose of the research was to acquire a 3D model of the trench at the end of the excavations and determine its potential as a registration method to adopt overall the site as an alternative to the conventional 2D measured drawings. The selected trenches of the LE site exceptionally present at the same time both some ashlar, rubble stone and brick masonry, and archaeological features of a Late Roman potter's workshop such as clay deposits and kilns [27] and were therefore assumed appropriate for a challenging trial of the method.

Figure 3.2 : Aerial view of the 2012-2013 excavation area to the East of the Neon-Library (roofed building on the left). The trench code is named ‘LE’ (Library East).

3.2 Applied Methodology

Structure from motion (SfM) is a computer vision technique that detects correlating feature points, using the well-known SIFT algorithm or a similar one, between overlapping images, and uses these points to determine the position and orientation of the camera at the moment of image acquisition [28, 29]. After detecting a set of feature points for every photograph and matching these points throughout the multiple overlapped images, the locations of these feature points can be calculated as a sparse 3D point cloud that represents the geometry/structure of the scene in a local coordinate frame [28, 30, 31]. This method has attracted great interest in recent years and many software packages, commercial as well as non-commercial, use SfM and dense stereo-reconstruction algorithms such as Autodesk 123D Catch [32], Automatic Reconstruction Conduit (ARC 3D) [33], Bundler [34], PhotoModeler Scanner [35], Photosynth [36] or VisualSFM [37]. In this study Photoscan Professional [38], developed by the Russian company Agisoft LLC., is employed.

After computing the positions of the cameras using SfM algorithm, the software combines the SfM approach with a variety of dense multi-view stereo (MVS) algorithms that enable the computation of a 3D dense point cloud which may contain millions of points of the observed area. Additionally, each model vertex color is determined due to calculation of the average value of the corresponding pixel values from the source photographs [40]. In the next step this dense point cloud is triangulated after pre-processing to reduce the large amount of vertices. As a result of this step, detailed polygonal meshed models – according to the image resolution and desired density – from the previously calculated dense point clouds are genrated [28, 30, 39]. It may be necessary to edit the mesh using tools such as mesh decimation, removal of detached components, the closing of holes in the mesh, etc. [40]. In the final step, the mesh can be textured in several modes in the software.

However, the created model is neither scaled nor oriented. In other words: the model is conveyed in its own local coordinate framework. The geo-referencing process is based on either ground control point (marker) coordinates or camera coordinates. The camera positioning method is faster than placing ground control points manually, however it is generally more accurate [40]. At least three ground control points of which the X, Y and Z coordinates are known must be used to geo-reference the model using the similarity transformation method. Ground control points can be imported into Photoscan and these reference points can be marked directly to the model or to photographs which contain the related ground control points. Another way to scale a model, without orientation, is by using a base distance, which allows an extraction of the metric information of the scaled model. Scaled but not oriented models are generally useful for single and individual objects like stones, sculptures, etc. Models of these kinds of objects can be scaled with a base distance easily and precisely and can be oriented manually to generate ortho-images.

There is one optional step, so called optimization, to adjust camera positions and consequentely sparse point cloud using ground control points. After placing the ground control points to their exact place in the photographs, camera positions can be adjusted using an optimization tool. It is observed that optimization process increases the accuracy relatively in larger areas. This step should be executed after the photograph alignment process.

3.3 Field and Office Works

In this section, the image based 3D reconstruction method to document the LE trenches is described detailedly. Field works will be described under the section of Data Acquisition, which consists of measuring the ground control points and taking photographs of the relevant area. Afterwards, this thesis will describe how the collected data are processed. The data processing was performed with Geforce GTX 770M 3 GB GPU, Intel(R) Core (TM) i7-4700MQ CPU and a 64 bit operating system (windows 7).

3.3.1 Data Acquisition

The data acquisition step can be classified into two sections: mounting and measuring the ground control points, and taking photographs of the relevant area adequately.

The targets to be used as ground control points are generated considering that they need to be visible decently in the photographs, and that they should be generated easily and numerously. A 16x12 centimeters sized target (Figure 3.8) was chosen to be used as ground control points. The excavation site that had to be documented in 3D was covered with 27 ground control points randomly and carefully as they wouldn’t hide any important details. After mounting the ground control points, all the points were measured by a GeoMax Zoom 30 total station [41] (Figure 3.3) in a local coordinate system. These control points are used as reference points to obtain absolute 3D geo-referencing of the model and they are essential in order to be able to test the accuracy of the model.

After the measuring process, photographs were taken using a 12.9 MP Nikon D5000 digital camera (Figure 3.3). Taking photographs is the most essential step since the method is based on overlapping photographs. The photographs should cover the relevant area in ways that there won't be any blind zones, and they should be taken as described in Figure 3.4. Optimized overlapping ratios for aerial photography are %60 for side, and %80 for forward, however it may be hard to accomplish in practice for complex areas such as archaelogical trenches. Another important matter when it comes to taking photographs is noise occurance caused mainly by bad photography. In order to reduce the noise, there are some recommendations about how to take and use photographs:

- Raw data which are converted to TIFF files with the best resolution possible should be used; the ISO value should preferably be the lowest.
- Aperture value and shutter speed should be chosen to result in not blurred, sharp photographs.
- It should be avoided to take photographs of shiny, mirroring, transparent or moving objects.

Figure 3.3 : Nikon D5000 digital camera and GeoMax Zoom 30 total station.

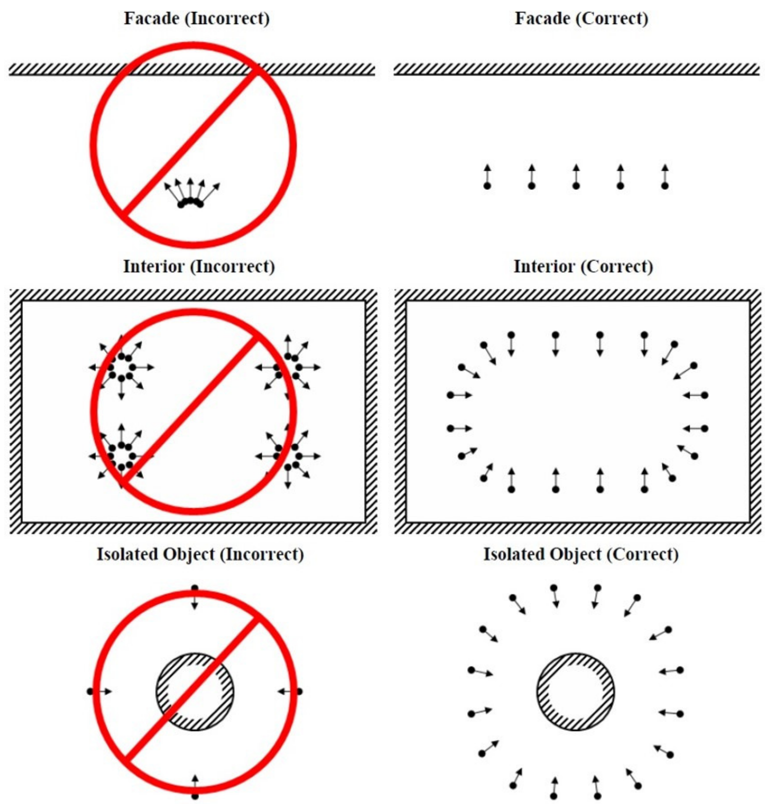

Figure 3.4 : Instructions for proper photography in order to reconstruct 3D models.

In this case study, the photographs were taken in three ways to avoid any blind zones: top-view images, general view images, and images of details. To be able to take top-view photographs of the site, the camera was placed on a 2 to 6 meters long extendable photograph-pole, one person has to hold the pole steady and align the camera position parallel to the surface as much as possible, whereas another person holds the remote control and gets the images (Figure 3.5). These top-view photographs are necessary to build the model more accurately and detailedy as well as to produce a proper ortho-image of the site. General view photographs of the subject area were also taken. Important objects such as walls, potter's kiln, workshop rooms etc. were photographed more in detail to make them more visible and clear in the model. The images were checked to avoid any problem that may be caused by taking photographs. Blurred images were eliminated before the images were processed, and an image set was prepared which covers the subject area adequately.

Figure 3.5 : Aligning camera position with the surface and taking top-view photographs.

3.3.2 Camera Calibration

Although it is not imperative to have the calibration report of the camera to create the 3D model, PhotoScan produced a user friendly module, called Agisoft Lens, to calculate the calibration report of any digital camera.

Agisoft Lens is an automatic lens calibration software, which uses LCD screens as a calibration target. It allows an estimation of the full camera calibration matrix, including non-linear distortion coefficients. Agisoft Lens estimates the following camera calibration parameters:

- f_x, f_y - focal length,
- c_x, c_y - principal point's coordinates,
- K_1, K_2, K_3, P_1, P_2 - radial and tangential distortion coefficients, using Brown's distortion model. [42]

Camera calibration parameters for Nikon D5000 were calculated using Agisoft Lens before image processing. The results are shown below:

° fx = 3.1691887196458433e+003
° fy = 3.1691887196458433e+003
° cx = 2.1435000000000000e+003
° cy = 1.4235000000000000e+003
° K1 = -1.2404056909583376e-002
° K2 = -4.2838523069249736e-003

- K3 = 9.8477232864560751e-003
- P1 = -7.0101113665503275e-004
- P2 = -1.0112441422884906e-003

3.3.3 Image Processing

The software creates a 3D model automatically in four steps: i) the alignment and optimization of the photographs, ii) dense point cloud generation, iii) building polygonal mesh and, iv) building texture. Before the alignment of the photographs there is one pre-processing step called "masking the photographs" (Figure 3.7). Masks are used in PhotoScan to specify the areas on the photographs which will be evaluated and can otherwise be confusing to the program or lead to incorrect reconstruction results [40]. Masking areas where “moving objects” (e.g. shadows or displaced objects) occur, where information about the texture of objects is lacking (e.g. sky and shiny objects) or where there is little variation in texture (e.g. full white objects), can be useful to produce higher quality models. Photographs that only depict zones without texture or “moving objects” can simply be omitted. The enabling, disabling or masking of (parts of) photographs can be adjusted in any stage of the process [40, 43].

3.3.3.1 The alignment of photographs and optimization process

After masking the necessary parts of the photographs, which is not an imperative step for alignment, the first step is performed. In this step, PhotoScan first uses SIFT or a similar algorithm to determine the feature points (Figure 3.6), then a SfM approach to calculate relative orientation of the camera position at the moment of image acquisition and the internal camera parameters (if these parameters were not computed during the camera calibration step), thereby matching the feature points. In this step there are three levels (low, medium and high) to scale the accuracy of calculating the positions of the cameras, which is directly correlated to number of the feature points, the resolution and quality of images. While the software uses the original image size with high accuracy setting, original image is downscaled by factor of 2 times by each side for medium accuracy setting, and by further 4 times by each side for low accuracy setting [40].

Figure 3.6 : Determined feature points on two overlapped images (blue ones were matched succesfully while white ones couldn’t be matched).

For 12.9 MP photographs, the software determines up to 5000 “key points” for low accuracy, up to 21000 “key points” for medium accuracy and up to 40000 (key point limit for default settings) “key points” for high accuracy. The software enables to change the key point limit as well. As a conclusion of this process, 281858 feature points were matched in less than half an hour and represented as a sparse point cloud. It is visually observed that all the photographs are aligned successfully (Figure 3.7).

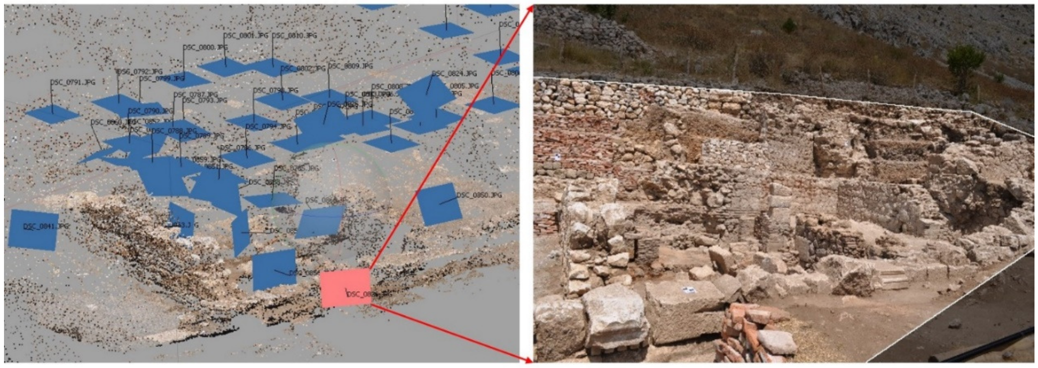

Figure 3.7 : Left: Based on a set of oblique and top-view overlapping images, PhotoScan calculated the relative camera positions and a point cloud. Right: The shadowed area is masked and extracted from photographs and also from image processing.

In this project, 27 ground control points were mounted to the relevant area randomly and measured by a totalstation in a local coordinate frame. Coordinates of the ground control points were imported into photoscan software and all of them placed to their exact positions for each photographs (Figure 3.8).

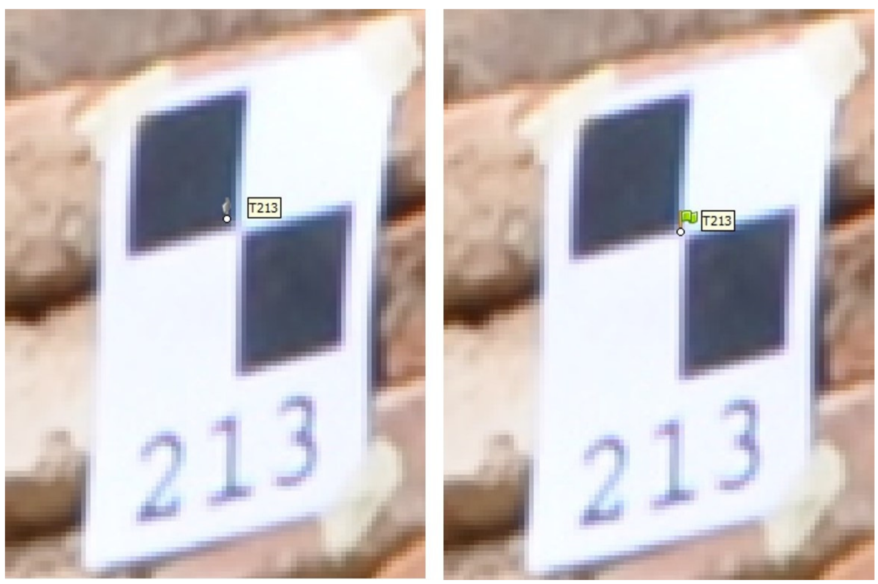

Figure 3.8 : Before and after replacing the ground control points.

After the replacement process, software calculated the adjusted positions of the cameras in few seconds and fixed the sparse point cloud accordig to the new positions. How the optimization process effects the accuracy is represented in the result section.

3.3.3.2 Dense point cloud generation

In the second step – which also calculates the colour for each model vertex and stores it as an attribute – a 3D coloured dense point cloud of the excavation site is built by using dense multi-view stereo-matching algorithms [43]. The software calculates depth information for each camera based on the estimated camera positions, using MVS algorithms, and creates a dense point cloud which contains millions of coloured vertices. Generated point cloud can be edited and classified or exported to an external tool.

The only difference about the accuracy setting between the photograph alignment section and the dense point cloud generation is; while the original image size is used for ultra high quality setting in dense point cloud generation, it is used for high accuracy setting in photograph alignment. The original image size will be downscaled by factor 4 (2 times by each side), respectively for each lower quality settings. [40]

The software enables three filtering algorithms answering different kind of projects: if the geometry of the scene to be reconstructed is complex with small details, then it is recommended to apply the mild depth filtering mode. If the area does not contain small details, then it is preferable to choose the aggressive depth filtering mode. The moderate depth filtering mode results between the mild and aggressive approaches [40]. The computation time largely depends on the resolution and the quantity of the used imagery and the level of detail wanted in the geometric model [43].

The mild setting for depth filtering options and high setting for quality options are prefered for this step. The data process took 8 hours. As a result of this step, 44376851 coloured points are generated. After eleminating wrong matched points, 44259090 points are left to create the polygonal mesh (Figure 3.9).

Figure 3.9 : The 3D sparse point cloud (top) created by using SfM algorithms, after the photograph alignment process, and the dense point cloud (bottom) created by using MVS algorithms, after the dense point cloud generation process.

3.3.3.3 Building polygonal mesh

In this step, there are three options to create the polygonal mesh from the dense point cloud: high, medium, and low. The number of the polygons to be generated is based on the number of the vertices which are created in the previous step: the ratio is 1/5 for high, 1/15 for medium, and 1/45 for low. The software also enables users to determine the target number of polygons in the final mesh [40].

The software also specifies two types of surface for this step; arbitrary surface and height field surface. Arbitrary surface type can be used for the modeling of any kind of object without any assumptions. Therefore the software consumes a very large amount of memory. On the other hand, the height field surface type is optimized for the modeling of planar surfaces. Consequently it requires a lower amount of memory and allows for larger data sets processing. [40]

In this project, 6632790 faces and 3322054 vertices were created in less than 1 hour, with the options of high polygon count and arbitrary surface type (Figure 3.10).

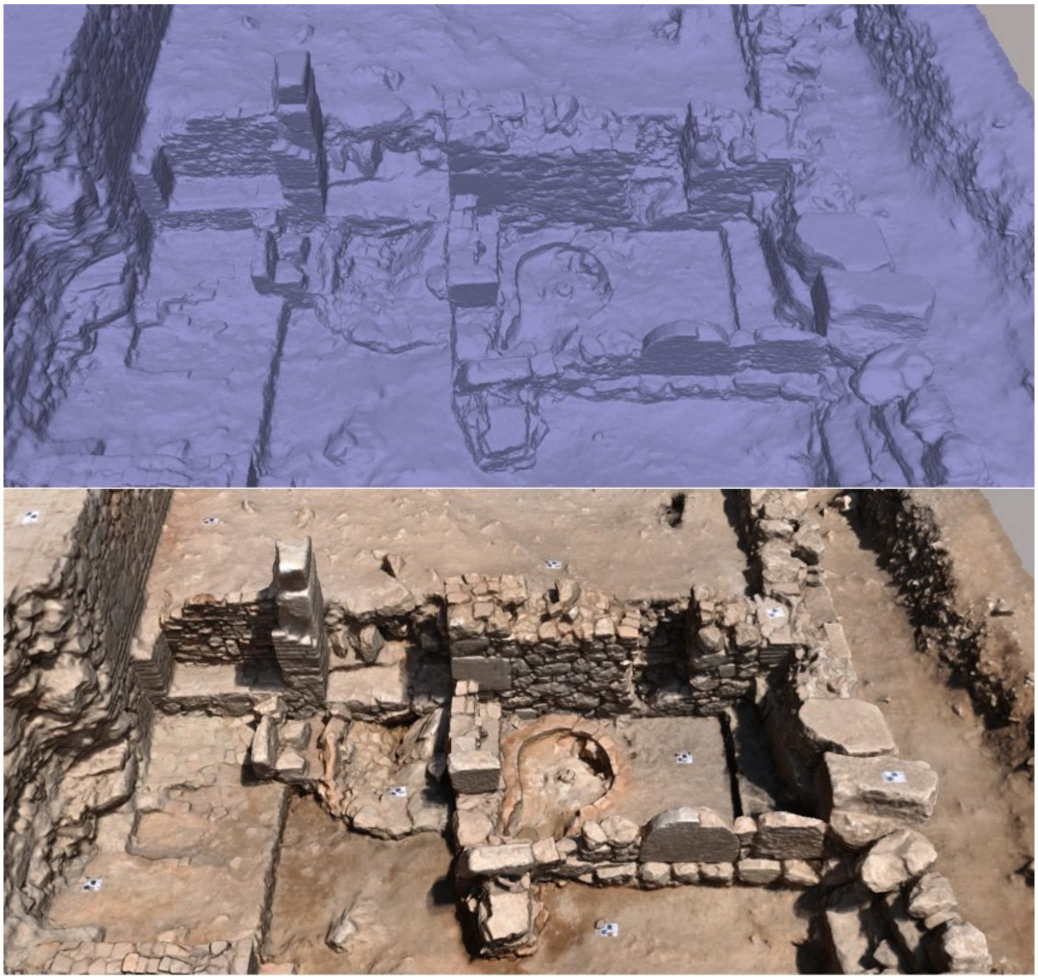

Figure 3.10 : Polygonal mesh of the LE trench, visualized in shaded (top) mode and solid (bottom) mode.

3.3.3.4 Building texture

For the last step of the general workflow of the software, photoscan allows to build a photo-realistic texture for the 3D model. In this step, a so-called texture atlas which consists coordinates of each model vertex, is calculated from one or more images. These coordinates are used to map the texture image onto the 3D model surface. Although this step is not necessary to create a DEM or ortho-image, a texture image with adequate resolution to visualize the details may very useful for 3D animation purposes and also to identify the reference points [43].

The software enables multiple mapping modes for different objects or purposes. Generic mapping mode for arbitary objects, adaptive ortho-photo mapping mode for vertical and planar surfaces, ortho-photo mapping mode for planar surfaces, spherical mapping mode for round objects [40].

The generic mapping mode was prefered for this study. Building the model texture took less than 10 minutes and shown at Figure 3.11.

Figure 3.11 : 3D model of the LE trench after building texture process.

3.4 Results

The image-based 3D documentation technique performed at the excavation site east of Neon Library in Sagalassos, 2013 campaign gave the following results:

Ninety six images taken with the Nikon D5000 camera were used to produce a 3D model of the site. Afterwards, 281858 feature points were matched. The generated dense point cloud consists 44259090 points. 6632790 faces and 3322054 vertices forms the mesh. The absolute geo-referencing was performed by using 27 ground control points. The accuracy of the model is represented in Table 3.1 and top view ortho-image represents the error vectors in Figure 3.12. A digital elevation model of the releavent area is also created (Figure 3.13).

Table 3.1 : The accuracy of the model is calculated by a differential between Real and Estimated coordinates and shown at the bottom of the table (in meters). The total RMSE and the RMSE for the x-, y-, and z-coordinates are presented at the bottom of the table.

GCP	Real x	Real y	Real z	Est. X	Est. Y	Est. Z	RMS (X)	RMS (Y)	RMS (Z)	RMS Error (m)	(without optimization)
T100	2499.776	2686.385	1544.269	2499.773	2686.389	1544.264	-0.003	0.004	-0.005	0.007	0.013
T101	2497.968	2686.649	1543.347	2497.961	2686.653	1543.354	-0.007	0.004	0.007	0.011	0.011
T102	2500.695	2691.875	1543.434	2500.679	2691.881	1543.429	-0.016	0.006	-0.005	0.018	0.019
T103	2501.798	2687.416	1544.548	2501.801	2687.415	1544.548	0.003	-0.001	0.000	0.003	0.005
T104	2503.515	2688.852	1544.532	2503.517	2688.854	1544.532	0.002	0.002	0.000	0.003	0.003
T105	2506.968	2689.075	1544.467	2506.970	2689.079	1544.466	0.002	0.004	-0.001	0.004	0.009
T106	2508.391	2689.626	1545.963	2508.396	2689.633	1545.968	0.005	0.007	0.005	0.010	0.014
T107	2507.892	2691.802	1546.142	2507.899	2691.801	1546.146	0.007	-0.001	0.004	0.008	0.017
T108	2500.094	2689.379	1543.328	2500.097	2689.380	1543.318	0.003	0.001	-0.010	0.010	0.011
T116	2502.233	2689.306	1543.421	2502.235	2689.308	1543.415	0.002	0.002	-0.006	0.007	0.009
T136	2503.155	2696.063	1546.098	2503.159	2696.064	1546.103	0.004	0.001	0.005	0.007	0.010
T137	2500.536	2695.103	1546.061	2500.540	2695.100	1546.064	0.004	-0.003	0.003	0.006	0.009
T138	2498.049	2694.596	1546.039	2498.054	2694.587	1546.041	0.005	-0.009	0.002	0.010	0.015
T199	2506.286	2691.732	1544.558	2506.286	2691.726	1544.565	0.000	-0.006	0.007	0.009	0.014

Table 3.1 (continued) : The accuracy of the model is calculated by a differential between Real and Estimated coordinates and shown at the bottom of the table (in meters). The total RMSE and the RMSE for the x-, y-, and z-coordinates are presented at the bottom of the table.

GCP	Real x	Real y	Real z	Est. X	Est. Y	Est. Z	RMS (X)	RMS (Y)	RMS (Z)	RMS Error (m)	(without optimization)
T213	2495.269	2693.621	1545.865	2495.269	2693.621	1545.851	0.000	0.000	-0.014	0.014	0.017
T214	2502.400	2694.977	1544.752	2502.402	2694.979	1544.757	0.002	0.002	0.005	0.006	0.010
T215	2496.217	2692.085	1544.947	2496.214	2692.078	1544.957	-0.003	-0.007	0.010	0.012	0.024
T216	2495.893	2689.931	1543.853	2495.886	2689.936	1543.853	-0.007	0.005	0.000	0.009	0.005
T217	2503.439	2691.277	1544.478	2503.446	2691.281	1544.479	0.007	0.004	0.001	0.008	0.008
T218	2496.964	2688.473	1543.468	2496.961	2688.474	1543.480	-0.003	0.001	0.012	0.013	0.014
T219	2498.534	2693.897	1543.636	2498.531	2693.894	1543.640	-0.003	-0.003	0.004	0.006	0.010
T236	2506.225	2693.579	1546.947	2506.227	2693.577	1546.952	0.002	-0.002	0.005	0.006	0.013
T237	2506.046	2695.785	1545.937	2506.046	2695.781	1545.947	0.000	-0.004	0.010	0.010	0.011
T238	2504.403	2697.095	1547.556	2504.406	2697.091	1547.547	0.003	-0.004	-0.009	0.010	0.012
T500	2503.748	2696.158	1545.996	2503.745	2696.154	1545.987	-0.003	-0.004	-0.009	0.010	0.009
T501	2497.940	2695.301	1547.104	2497.935	2695.297	1547.094	-0.005	-0.004	-0.010	0.012	0.009
T502	2506.378	2692.350	1546.135	2506.376	2692.354	1546.123	-0.002	0.004	-0.012	0.013	0.020
							0.005	**0.004**	**0.007**	**0.010**	**0.013**

Figure 3.12 : The accuracy of the model is represented as an ortho-image including error vectors.

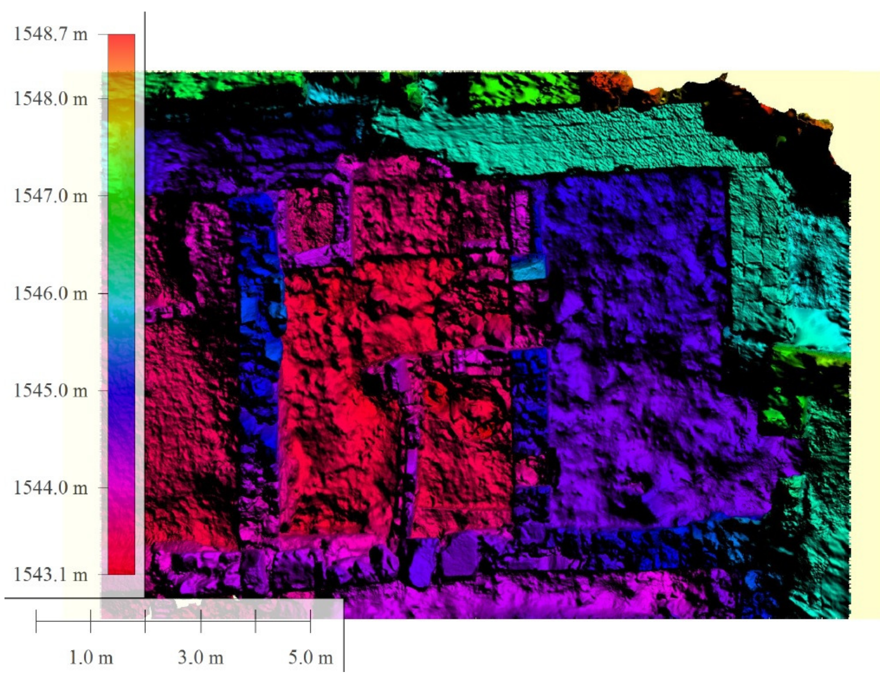

Figure 3.13 : Digital elevation model of the final situation of the LE trench.

Based on these results, a highly accurate and high resolution image based 3D reconstruction of the final situation of the excavation site of LE is produced. The final product can be exported to 2D ortho-images from any viewpoint desired. Architectural recording can be performed using these ortho-images by digitizing them in a CAD environment. This method allows faster and more cost efficient architectural recording than conventional and topographic methods.

4. CONCLUSION AND RECOMMENDATIONS

In this study, an image-based 3D point cloud technique, which allows productive, fast and cost efficient 3D modelling, is used to record the LE excavation site of Sagalassos, at the end of the 2013 campaign. To be able to perform the method, a 12.3 MP digital camera, a reflectorless total station instrument, and a low cost commercial photogrammetric software are used. 96 images were taken and used to build 3D geometry of the site, and 27 ground control points which were measured by a reflectorless total station were used for the adjustment of the camera positions and orientations, and absolute geo-referencing of the textured model. While the photographing and measuring process took around 2 hours, processing 96 images took around 10 hours. This means the whole excavation area was reconstructed in 3D approximately in 12 hours. The accuracy of the excavation site's 3D model and resolution of the ortho-images produced from the model proved that this technique is capable for recording cultural heritage and is more efficient than topographic and conventional recording methods considering the parameters of cost, time and accuracy.

In addition to successfully documenting the final stage of excavation sites, this method can also help building 3D surface models of all layers and understanding the three-dimensional relationships between those layers during the excavation. In other words, this method allows to demonstrate a whole excavation process in 3D.

This method enables the 3D modelling of almost any kind of objects; small or large, complex or plain. Therefore this technique can be used not only for documentation purposes, but for many others as well. For instance; individual architectural units can be modelled to carry out restitution/restoration or anastylosis projects of damaged or destroyed architectural structures in 2D (based on ortho-images) or 3D (based on textured models). Also large scale buildings like theaters can be modelled using low altitude imagery combined with terrestrial.

Another advantage of this method is that the workflow can be divided in two: field work and office work. So there is no need to be on the site as long as the field work is completed successfully. In limited excavation periods, this can bring great efficiency and continuity.

Of course there are some disadvantages like any other methods have. In case of a lack of coverage of the area, there will be some empty spots in the model. Bad data are unpredictable since they are not processed. Also, bad photography will cause large noise in the model.

Another unfavourable side of the method is the fact that it requires working with a very large amount of data sets. The software needs several photographs, preferably raw data format, and it creates a very large amount of data at the end of the process. If it is assumed that every site will be recorded using this method, it will be necessary to have enormous digital data storage to save the source and final data, unlike conventional and topographical techniques.

The biggest issue of this method is the usage limitation; some of the objects are not suitable to be modeled with this method. Transparent, shiny or reflective surface types give poor and meaningless results.

When we consider the advantages and disadvantages of the method in the context of the recording of excavation sites, it can be said that this method is highly preferable. Successful results gained in this study prove that the technique can be used for geometric documentation and many other purposes, smaller or larger scale. It is promising that obtaining 3D data will be helpful for interpretation and future studies.

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- (Eylül 2013 – Aralık 2014) Göze Üner Architects.
- (Temmuz 2009 – Eylül 2014) Sagalassos Arkeolojik Araştırma Projesi.