The Digital Michelangelo Project and the Forma Urbis Romae Project



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Executive summary









Atlas

Awakening

Bearded Youthful





Why scan the statues of Michelangelo?

Motivations

- push 3D scanning technology
- tool for art historians and conservators
- lasting archive

Technical goals

- scan a big statue \longrightarrow 5 meters
- capture chisel marks $\longrightarrow 1/4 \text{ mm}$

 $20,000^2$

 \approx 1 billion

20,000:1

Why capture chisel marks?



Day (Medici Chapel)

Scanner design

4 motorized axes

truss extensions for tall statues







laser, range camera, white light, and color camera

Laser triangulation rangefinding



Scanning St. Matthew



working in the museum

scanning geometry scanning color





Scanning a large object



• calibrated motions

- pitch (yellow)
- pan (blue)
- horizontal translation (orange)

- uncalibrated motions
 - vertical translation
 - remounting the scan head
 - moving the entire gantry

Our scan of St. Matthew



- 104 scans
- 800 million polygons
- 4,000 color images
- 15 gigabytes
- 1 week of scanning

Post-processing pipeline



• steps

- 1. aligning the scans
- 2. combining aligned scans
- 3. filling holes







artificial surface reflectance



estimated diffuse reflectance



accessibility shading

Visualizing inscribed surfaces (with application to cuneiform tablets)



(from Nissen, Damerow, Englund)

- a photograph can only show one side of a tablet at a time – hard to show tablet edges
- raking illumination favors strokes of one orientation
 - need multiple photographs



original tablet

• UR III dynasty (2100 B.C.)

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fit a curved surface patch to the curved tablet
error in fit → relief map



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Scanning the David





height of gantry: weight of gantry: 7.5 meters800 kilograms

Scanning the David



- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 32 gigabytes
- 30 nights of scanning
- 22 people





The importance of viewpoint





classic 3/4 view

left profile



face-on view

The importance of lighting





lit from above

lit from below

Some uses for these models

• unique views of the statues

A kiosk for viewing 3D models



- PC + graphics card + custom software
- arcade-quality buttons and trackballs
- no touch screen, no menus, no instructions to read



Some uses for these models

• unique views of the statues

• permanent archive

Some uses for these models

- unique views of the statues
- permanent archive
- physical replicas

Replica of Michelangelo's David (20 cm tall)



Some uses for these models

- unique views of the statues
- permanent archive
- physical replicas
- conservation

Cleaning the David



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EXPLORING DAVID

DIAGNOSTIC TESTS AND STATE OF CONSERVATION














Digital Michelangelo Project Grand Catalog



<u>Digital Michelangelo Project Main Page</u> <u>Help file</u>

Statue Name	Atlas	Awakening	Barbuto	
Rendering				
README	Atlas README			
Calibration	old.calib	default	old.calib	
<u>Raw SD Data</u>	atlas-sd-1.tar.gz (215 MB) atlas-sd-2.tar.gz (279 MB) atlas-sd-3.tar.gz (184 MB) atlas-sd-4.tar.gz (116 MB)	<u>awakening-sd-1.tar.gz (248 MB)</u> awakening-sd-2.tar.gz (276 MB) awakening-sd-3.tar.gz (102 MB) awakening-sd-4.tar.gz (78.8 MB)	<u>barbuto-sd-1.tar.gz (224 MB)</u> barbuto-sd-2.tar.gz (222 MB) barbuto-sd-3.tar.gz (132 MB)	
<u>Modelmaker Data</u>	atlas-modelmaker-1.tar.gz (261 MB) atlas-modelmaker-2.tar.gz (411 MB) atlas-modelmaker-3.tar.gz (294 MB) atlas-modelmaker-4.tar.gz (340 MB) atlas-modelmaker-5.tar.gz (177 MB) atlas-modelmaker-6.tar.gz (241 MB)	awakening-modelmaker-1.tar.gz (230 MB)	<u>barbuto-modelmaker-1.tar.qz (186 M</u> barbuto-modelmaker-2.tar.qz (187 M	

Solving the puzzle of the Forma Urbis Romae



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Rome, circa 200 AD



Forum Pacis

Forma Urbis Romae (form of the city of Rome)



- carved 207 A.D.
- 60 wide x 45 feet high
- marble, 4 inches thick
- showed the entire city at 1:240
- most important map of ancient Rome that still exists

Fragment # 010g



Solving the jigsaw puzzle



- 1,186 fragments
 - 200 identified
 - 600 unidentified
 - 400 unincised
- 15% of map remains
 - but strongly clustered
 - 1 out of 3 fragments remain in the central core of the city
- fitting the remaining pieces together has been an open problem for 500 years



uncrating...



positioning...



scanning...



aligning...

Fragment #642





3D model

color photograph

Sizes of 3D digital archives

model	polygon count
Americo Vespuccio, commercial model by De Espona	224,000
Trajan's Forum, reconstruction by B. Frischer (UCLA)	1,950,000
Santa Cristina Crypt, Carpignano, laser scan by A. Beraldin (NRC)	12,000,000
Michelangelo's David, laser scan by M. Levoy et al. (Stanford)	56,000,000
1,186 fragments of the FUR	8,000,000,000



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Home •	Project • Ma	p • Datab	ase •	Glossary •	Bibliography • People • Links •	
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	100					
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					Neronian branch of the Agua Chudia (arear Neronian)	
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202	54	54	2	amooth	Temple to the Dedied Chodias (seeplaw dry Claud)	di.
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222	516	55	2	amooth	Temple to the Deifed Claudia (seeplaw dra Claudi	61.
00244	5.48	5.48	22	second	Temple to the Defind Chodias (resplace drif Cloud)	11
2024	5.6	14	22	not preserved	Temple to the Dedied Classics (seeplaw dri/ Claud)	11
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927abc6(*)	744	7 a-d	21	mooth	Circus Maximus (circus Maximus) with Arch of Titus (arcus Int Septicodum (Septicodum)	
002402	74	74	25	mooth	Theps (advenue) south of the Circus Maximus (rives: Maximus	÷ .
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00860*0	15	85	24	meeth	Cerea Manimus (viroar Manimus)	
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<u>6107</u>	30.6	10 f	22	month	Section of the Island neighborhood (Judana)	
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600a	010 .	20 m	22	meeth	Headquarters of a collegium (criteria(C) off the View Batuei (crear Saluer) in the Islane neighborhood (Saluer)	
2120808	10 are	10 ++	22	amouth	Section of the Subura neighborhood (Jadura) including the Portious of Livia (southur Linne) and the Batto of Topias (dormae Frates)	6
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Online archive



- scholar's version (http://rockpile.stanford.edu)

 viewable and downloadable 3D models
 high-resolution color photographs
 requires permission from Stanford and Rome
- public version (http://formaurbis.stanford.edu)
 - viewable but not downloadable 3D models
 - medium-resolution photographs
 - no license required

ScanView remote rendering system [Koller, SIGGRAPH 2004]





- high-res model stored only on server at Stanford
- client program allows manipulation of low-res model, queries server for rendered image on "mouse up" event
- one server can handle 10 queries per second = 50 users
- 10,000 downloads of client program in last 24 months

The puzzle as it now stands



Clues for solving the puzzle

- incised lines
- incision characteristics
- marble veining
- fragment thickness
- shapes of fractured surfaces
- rough / smooth bottom surface
- straight sides, indicating slab boundaries
- location and shapes of clamp holes
- the wall: slab layout, clamp holes, stucco
- archaeological evidence

Algorithms for solving the puzzle

• fragment-to-fragment clustering

Fragments fn8 & 281





- 1. slab edges
 - 2. fragment thickness
 - 3. veining direction (relative to slab edge)
 - 4. architectural axis (relative to slab edge)

Algorithms for solving the puzzle

• fragment-to-fragment clustering

• fragment-to-fragment matching





A match in the Circus Maximus



Known fragments of the Circus Maxium



We expected a "marble lock"





fragment 351

fragment fn9

so we reopened the crates...



...and we found one!







Fracture geometry



2D fracture boundaries



3D fracture surfaces

Red Sequence: L5, L7, L7, L9, L13, R2, ... Green Sequence: L1, L3, L8, L8, R3, R3, ...

Algorithms for solving the puzzle

- fragment-to-fragment clustering
- fragment-to-fragment matching
- fragment-to-wall constraints

Riverfront fragments



348



27c





27b

32i



Fragment 348 in context






Clamp holes



Fragment 421





High Probability Match

Med. Probability Match

Low Probability Match

1		2		3			4			5		6	. 7			8					10		
11	1	2		13			14			15				6		17		18		<i>111</i> 4,			
21			22			23			24		2	25		26		<u>,</u>		28		29		,	
30			31			32			33				34		<u> </u>						37		
39	40	41	42	43	44	4	5	46	47	48	49		50	51	52	53	54	55	56	57	58		
60			61 62		2		63		64			65		66		67			68		69		
70	71	I 72	2 7	3	74	75	76	7	77	78 7	9 8	0	81	82	83	84	85	86	87	88	89	90	
91			92 93			; 9		94			5		96		97		98		8			99	
100	10	1 10	12 1	03	104	10	5 10)6	107	108	109	1	10	111	112	113	114	11:	5 11	6 11	7 1	18	
119 120			121			122		123			124		125		126		127			128	28 129		
130	131	132	2 133	3 13	34	135	136	13'	7 13	38 13	9 14	40	141	142	143	144	145	146	147	148	149	150	

Match Fragment 421 with 475!



Wall Feature Matching: example results for fr. 421+475

High Probability Match

Med. Probability Match

Low Probability Match

	1 2 3				5		4			2) :	: /				:	9		10			
11		12 13				14				15			16		17	17 18		3		19			
21				22			2	23				25		26		27			28		29		
30				31			3	2		33			34	34		35				31		7	
39	40	41	4	42	43	44	45	5 4	6	47	48	49	50	51	52	53	54	55	56	57	58	3	
	60		61	61		62		6	63		64		65	5	66		67			68		69	
70	7	1 7	72	73	7	4	75	76	77	7	8 79	80	81	82	83	84	85	86	87	88	89	90	
91			92	92 93		93	9		94)4			96		97		9		8	8			
100	10	1 1	02	10	3 1	104	105	10	5 10)7	108	109	110	111	112	113	114	¥ 11	5 11	6 1	17	118	
-119	119 120			121			122			123		124		125		126		127		128		129	
130	131	13	2	133	13	4 1	135	136	137	138	3 139	9 14	0 141	142	143	144	145	146	147	148	149	150	

The Aventine Hill



The nature of computer-generated matches

• high probability

- Fragments 28a, 34b, fn23 (Via Campana-Portuensis, Naumachia Augusti)
- Fragments 156, 667
- Fragments fn9, 351 (Circus Maximus)
- Fragments 28a, 150 (Via Campana-Portuensis)
- Fragments 92, 138 (Transtiberim)
- Fragments 330, 354 (Transtiberim?)
- Fragments 37Ail, 576 (Transtiberim)

• medium probability

Fragment 421.txt

clampholes a4-2:0, a4-15:1 - no, clampholes on bottom clampholes a4-5:0, a4-3:1 - maybe clampholes b4-1:0, b3-18:1 - no, occupied by fragment 10 clampholes b4-2:0, b4-3:1 - no, clampholes on bottom clampholes c2-11:0, c2-9:1 -no, no tasselli on bottom clampholes c3-17:0, c3-16:1 -no, between 2 slabs clampholes c4-27:0, c4-18:1 - no, between 2 slabs clampholes a7-13:0, a7-12:1 - maybe? clampholes a8-11:0, a8-8:1 - no, tassello on bottom clampholes a8-13:0, a8-11:1 - no, tassello on bottom clampholes a8-16:0, a8-12:1 - no, many problems! clampholes a9-6:0, a9-5:1 - maybe? clampholes a10-1:0, a9-15:1 - maybe? clampholes b6-2:0, b6-1:1 - no, occupied! clampholes b10-1:0, b9-2:1 - maybe? clampholes b10-2:0, b10-3:1 - no, clampholes on bottom clampholes c9-23:0, c9-25:1 - no, between 2 slabs

Fragment 711.txt

clamphole a2-1, tassello a2 (4) no, crosses slab boundary clamphole a2-2, tassello a2 (1) no, same clamphole a3-8, tassello a4 (3) no, same clamphole a4-1, tassello a4 (2) clamphole a4-2, tassello a4 (1) no, same clamphole a4-5, tassello a4,a5 (3) no, same clamphole a4-7, tassello a4,a5 (2) clamphole a4-7, tassello a4,a5 (3) clamphole a5-11, tassello a5,a6 (2) clamphole a5-11, tassello a5, a6 (3) clamphole b3-9, tassello b3 (2) clamphole b3-10, tassello b3 (3) clamphole b3-13, tassello b3 (1) clamphole b3-15, tassello b4-1 (3) clamphole b4-1, tassello b4-2 (2) clamphole b4-1, tassello b4-2 (3) clamphole b4-2, tassello b4-2 (1) clamphole b4-6, tassello b4-1 (2)

MaxScore=5.5: 4,2,45 frags/102.txt frags/103.txt MaxScore=2: 5,6,50 MaxScore=1: 2,0,5 frags/104.txt frags/105.txt MaxScore=-99999: 2,0,5 frags/106.txt MaxScore=3: 4.0.50 frags/107.txt MaxScore=-99999: 4,0,50 MaxScore=5: 3,17,40 frags/108ab.txt frags/109.txt MaxScore=-99999: 3,17,40 frags/10Aa.txt MaxScore=6.5: 3.10.50 frags/10Ab.txt MaxScore=4: 4.1.50 frags/10aa.txt MaxScore=6: 3.9.45 frags/10abcdeAaAb.txt MaxScore=8.5: 6,7,40 frags/10fgh.txt MaxScore=8.5: 0,17,30 frags/10ilmpqrs.txt MaxScore=8: 7,72,35 frags/10n.txt MaxScore=3: 3,8,40 MaxScore=6.5: 4,15,50 frags/10noaa.txt frags/10o.txt MaxScore=6.5: 3,25,45 frags/10p.txt MaxScore=5.5: 1,27,15 MaxScore=5: 3,9,50 frags/10q.txt MaxScore=3: 3,2,40 frags/10r.txt MaxScore=4: 5,5,50 frags/10s.txt frags/10tuv.txt MaxScore=6.5: 3,12,35 -5. 2 2 50

Algorithms for solving the puzzle

- fragment-to-fragment clustering
- fragment-to-fragment matching
- fragment-to-wall constraints
- fragment-to-city matching

Ludus Magnus – a gladiator training stadium



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forma urbis romae



In closing...

• strawman conclusions

 3D scanning will become faster and cheaper, but it will never become routine

Some statues may be "unscannable" (using optical methods)





In closing...

- strawman conclusions
 - 3D scanning will become faster and cheaper, but it will never become routine
 - automating geometric matching is easy, but automating high-level reasoning is hard

» Human archaeologists are still needed!

- questions for the future
 - What is the proper role for 3D scanning?

Creating digital libraries of 3D content



- 3D archives are large
- metadata data about data
- secure viewers for 3D models
- robust 3D digital watermarking

- viewing, measuring, extracting data
- indexing and searching 3D content
- insuring longevity for the archive

In closing...

- strawman conclusions
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 but automating high-level reasoning is hard

» Human archaeologists are still needed!

- questions for the future
 - What is the proper role for 3D scanning?
 - visualization versus analysis
 - Can 3D scanning aid field archaeology?

The team in Italy

(May/June, 1999)

• Faculty

- Prof. Marc Levoy

• Sovr. Communale

- Prof. Eugenio La Rocca
- Dott.ssa Laura Ferrea
- Dott.ssa Susanna Le Pera
- Dott.ssa Anna Somella

• Sponsors

- Interval Research
- Paul G. Allen Foundation for the Arts
- Stanford University
- Sovraintendenza Communale
- Mellon Foundation
- Pierluigi Zappacosta

• Staff

– Dr. Kari Pulli

• Computer Science students

- Sean Anderson
- Dave Koller
- Lucas Pereira
- Szymon Rusinkiewicz

• Additional software development

- Matt Ginzton
- James Davis
- Prof. Brian Curless (UW)

The team at Stanford (2001-2004)

• Faculty

- Prof. Marc Levoy
- Prof. Jennifer Trimble

• Classics students

- Margaret Butler
- Elizabeth Clevenger
- Jacob Denmark
- John Mandsager
- Andrew Martin
- Marden Nichols
- Matthew Shulman
- Lilla Toal

Sponsors

- National Science Foundation
- Stanford University
- United Parcel Service

• Staff

- Dr. Tina Najbjerg
- Dr. Steve Marschner

• Computer Science students

- Sha Sha Chu
- Natasha Gelfand
- Leslie Ikemoto
- David Koller
- Tricia Lee
- Francois-Marie Lefevere
- Austen McDonald
- Rene Patnode
- Nicolas Scapel
- Additional collaborators
 - Dott.ssa Claudia Cecamore



http://graphics.stanford.edu/projects/mich/ http://graphics.stanford.edu/projects/forma-urbis