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The Digital Sculpture Project

Applying 3D Scanning Techniques for the Morphological Comparison of Sculptures

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Abstract

Over the last decade, highly accurate mobile 3D measurement technologies have become available and are widely used now in industry and entertainment. In the cultural heritage field, various 3D pilot projects for conservation and restauration purposes have been initiated or completed already. My Digital Sculpture Project, started in November 2001, focuses on establishing an efficient workflow for creating high-resolution geometric models of both small and large plaster, terra-cotta and bronze sculptures, with a limited budget and a small support team, in improvised, non-laboratory situations and within narrow time windows, as encountered in the course of a significant series of museum visits all over Europe. Specific requirements and scanning strategies for scanning complex sculptures are discussed, along with a series of scanner tests. The article explains possible applications of 3D documentation methods, especially their relevance for comparative morphological analysis and issues of originality and authenticity. To demonstrate the use of 3D difference maps, this paper presents an exact and objective comparison of two monumental plasters of Auguste Rodin's 'Thinker', located in France and Poland respectively, conducted in December 2003.

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Studied Political and Social Sciences at the University of Amsterdam and the Free University, Berlin, 1975-1982

Publisher and author of www.rodin-web.org.

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Foreword and Acknowledgements

This article was written to demonstrate the relevance of 3D data capturing techniques for exact morphological comparison of sculptures, especially with regard to issues of originality and authenticity, and to report on my own activities in this field since November 2001.

This publication at Linköping University Electronic Press is meant to inform interested scholars and professional circles about the specific art-historical questions, emiprical methods and practical working programme I have developed, and shall allow for peer review and critique.

This publication presents for the first time the comparison of two original Thinker plasters in Strasbourg, France, and Poznan, Poland, in the form of a scientific article, as part of a broader effort to create an efficient, affordable procedure for producing highly accurate, complete 3D models of sculptures by Rodin and his contemporaries in non-laboratory situations, developing and employing a mobile documentation studio for short museum visits (1-3 days for each visit). The current working title of this larger project is “Digital Sculpture Project”. In the past, the names “Thinker Project” and “Rodin Virtual Sculpture Project” (or “Virtual Rodin Sculpture Project”) have been used as well, referring to specific aspects of these activities. The Digital Sculpture Project has evolved from my long-time fascination for the work of the French sculptor and draughtsman Auguste Rodin (1840-1917), an interest fuelled mainly by artistic and aesthetic motives. All activities have been financed on a strictly private basis. I hope that other initiatives may profit from the experiences and insights presented here, so that the treshold for applying 3D technology in museum situations is lowered.

At this place I would like to thank all persons, institutions and companies who have supported my work so far with information, comment, critique, practical and moral support: William Moore and Mary Reid at the MacLaren Center and David Schaff in Philadelphia, who were prepared to enter into complex discussions with me, Jacques Vilain, Director of the Musée Rodin, Paris, who explained the attitude of the Musée to me, Gary Snell, Director of Gruppo Mondiale Est, who ventured his point of view in lengthy telephone interviews, and Catherine Lampert, former Director of Whitechapel Art Gallery, who encouraged me to maintain an independent forum on the issues addressed at the Toronto Rodin Symposium. Thanks to Dr Bernd Breuckmann, Dr Hans-Peter Duwe and the team at Fa. Descam GmbH, who supplied me with equipment, software and services free of charge or at reduced prices, to all museum Curators and other staff, who permitted me to document works in their collection, to Prof. Jacques de Caso, San Francisco, and Dr Alain Beausire, Paris, who commented on various aspects of my efforts, to Marco Zajac and Stefanie Adolf, Minolta-3D, Langenhagen, Moritz Gaupp, Movingworld, Wessling, Peter Petrov, Basis Software, Moscow, Mike Davies, AGEO, David Hampton, E-Magine3D, Prof. John Cosmas, Brunel University and Angy Geary, Royal College of Art[1], all in London, and Aaron Bergstrom, North Dakota State University Archaeology Technologies Laboratory, who discussed their 3D scanning strategies with me. Thanks to all friends and assistants, who joined me on trips and participated in work sessions and informal gathering, supporting the project with their energy and interest: Simone and Uli Huber, Stefanie Prinz, Charlotte Harmsen, Judith Schmidt, Susanne Krueger, Doreen Dörfler, Katrin Schmid and others. A special thanks to my wife Borbála, who took actively part in my idea from the very beginning, to Alida Kreutzer and Esther Dieckhoff for all their help and inspiration along the way, and to Prof. Erik Sandewald and Peter Berkesand at Linköping University Electronic Press, who in the end made the publication of this paper possible at all.

Hans de Roos

Munich, in December 2004

1 After completing her own 3D research project on European polychrome sculpture, Angie Geary is now Senior Research Fellow at Camberwell College of Arts, UK.

1. The Nascency of the Digital Sulpture Project

1.1 The Rodin Symposium in Toronto

In June 2002, while expanding my collection overview for www.rodin-web.org, my independent online platform on life and work of Auguste Rodin, I learned about a planned donation of circa 50 Rodin plasters to the MacLaren Art Center in Barrie, Ontario, Canada. These items originated from the former Rudier Foundry and had come to the art market after the settlement of the company. A large number of these plasters had been collected in the 1990s by Gruppo Mondiale Est (G.M.E.), based in Treviso, Italy. Apart from organising exhibitions[2], Gruppo Mondiale Est also engages in producing and distributing posthumous casts from these plasters[3], this way competing with the posthumous casting programme by the Musée Rodin in Paris. In the course of my correspondence with William Moore, at that time Director of the MacLaren Art Center, I wrote an overview of the discussion on ethical aspects of posthumous casting. This outline was subsequently utilised to announce a Rodin Symposium held in Toronto on 6 November 2001, organised by the Royal Ontario Museum (R.O.M.). This conference focused on the question "Rodin – What Is

Uncrating the Rodin plasters in Barrie, March 2001.

2 "Rodin Plaster & Bronzes", 4 June – 8 Nov. 2000, Palazzo delle Prigioni Nuove; "New Exhibition of Auguste Rodin", 15 Dec. 1999 – 13 Febr. 2000, Palazzo Isolani; "Auguste Rodin Sculpture Exhibition", 1 Aug. – 7 Nov. 1999, Church St. Stae, Grand Canal, Venice.

3 These editions are currently promoted through the G.M.E. website www.rodin-art.com.

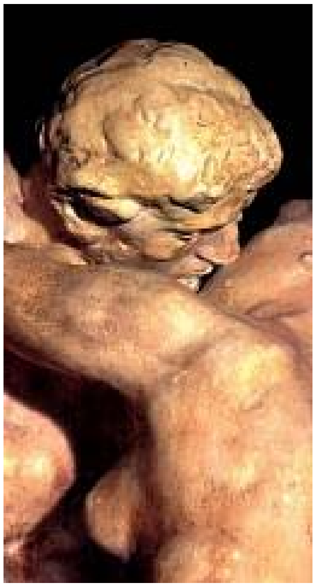
Toronto Symposium, 6. Nov. 2001. Photo: Alida Kreutzer.

Original?", to accompany the exhibition "From Plaster To Bronze" (20 Sept. 2001–17 March 2002), also at the R.O.M.

Already before the show opened, the quality of the plaster and bronze casts exhibited in Toronto was discussed internationally. In July 2002, the Musée Rodin in Paris launched a press release claiming that the exhibited plasters would not be original; the shown plaster collection would consist of so-called foundry plasters (*plâtres de fonderie*), that had been damaged by foundry work processes and for that reason would neither be appropriate as an object for public exhibition, nor as a model for further reproduction in bronze:

> "Il s'agit là de plâtres de fonderie usés, enduits d'agents de démoulage qui les amollissent encore plus, et dont certains sont des agrandissements postérieurs à la mort de l'artiste, et donc non voulus par Rodin. (...) Pour avoir attentivement étudié ce fonds, les responsables du musée Rodin continuent d'affirmer qu'il s'agit là de plâtres de fonderie usés, et qu'à partir de plâtres usés, on ne peut obtenir que des bronzes de piètre qualité. Ce fonds de plâtres et bronzes ne saurait en rien refléter la création de Rodin."[4]

4 Communiqué conjoint du Musée Rodin et de la Direction des Musées de France, July 2001. This text was mailed by the Musée Rodin to the author on 9 Oct. 2001.


Abraded ‚Kiss' plaster
Photo: M. Carrieri, G.M.E.

By comparing catalogue photos and personally visiting the exhbition at the Royal Ontario Museum I ascertained that some of the exhibited plaster casts actually showed clearly visible abrasions and discolourations, while others had almost pristine surfaces or could be identified as lifetime exhibition or presentation plasters, for example by engraved dedications to Rodin's friends and contemporaries.[5] I also found out that the accusation of displaying posthumous enlargements - an association with scandal that had once hit the Musée Rodin itself in 1919, regarding the enlargement of 'La Defense' for the Monument to Verdun[6] - did pertain only to a single Nijinski plaster, that was not included in the Toronto show.[7]

By email correspondance and telephone interviews with Jacques Vilain (Director of the Musée Rodin), Gary Snell (Director of the Gruppo Mondiale Est, pre-owner of the exhibited objects), William Moore and Mary Reid (Director respectively Curator of the MacLaren Art Center) I tried to collect more precise infomation on provenance, age and quality of the other plasters, in order to prepare my Symposium speech. Apart from general considerations of the definition of the original in Rodin's mode of production and a critical analysis of the various arguments launched in press articles, I presented a slideshow directly comparing the denounced items with similar sculptures in recognised museum collections.

5 For example, a medium size 'Eve' plaster is dedicated "A mon ami D". See condition report by Dr David Schaff and Mary Reid, 19 July 2000. A small plaster 'Head of Balzac' is dedicated to "Saumer", as personally demonstrated by Ms Reid to the author on 5 Nov. 2001 at the R.O.M.

6 See Albert E. Elsen, Rodin's 'Perfect Collaborator', Henri Lebossé, in: Rodin Rediscovered, National Gallery of Art, Washington, 1981, p. 256.

7 Confirmed by email by Jacques Vilain to the author, 12 Oct. 2001.

1.2 Establishing a classification of the MacLaren plasters

Because the precise backgrounds of the discussed plaster casts and the planned donation, as well as the true motives for the bitter confrontation between the French and the Canadian museums were not transparent even for the invited speakers, I continued to investigate the underlying facts after my return to Munich, especially by an intensive email correspondence with MacLaren Curator Mary Reid and Dr David Schaff, Senior Curator of the Toronto exhibition. In the course of this dialogue, the outline for a first scientific classification of the MacLaren plasters emerged.

In this extensive correspondence, I addressed vital questions insufficiently answered before and during the Symposium and by the written documentation finally supplied by the MacLaren Art Center: chain of ownership, the amount of damage actually showing on each plaster, their true date of production, and their status as first-generation plasters vs. duplicates.

1.3 Foundry plasters and duplicates

According to MacLaren staff, it was usual practice in 19th Century foundries to duplicate the plaster sent by the artist, to save this precious object from the wear and tear caused by repeated mould-making.[8] By replication processes, the sharp edges of the original plaster would be blurred; chemical agents used to separate the plaster from the mould would mollify and erode the surfaces to be reproduced; if a first-generation plaster was duplicated in order to prevent (further) damage, the fine detail of the first plaster could not be completely transferred to the next generation. The critics of the exhibition questioned the validity of a show presenting such foundry duplicates. In an extensive and highly critical article in the Toronto Globe And Mail,

8 Email by Mary Reid to the author, 4 Nov. 2001.

Saray Milroy referred to these items as “byproducts of industry” without intrinsic artistic value.[9]

Although the museum report by Dr David Schaff confirmed the duplicate status for the majority of exhibited plasters, Schaff believed ca. one-third of the items to be first-generation exhibition, studio or presentation plasters[10]. MacLaren Director William Moore defended the foundry plasters by suggesting Rodin would have cared about the quality of such plasters more than that of other items, for the very reason the foundry plasters functioned as a model for translation into bronze:

> “Clearly, the foundry plaster was extremely important to Rodin, for that was the plaster about which he cared the most! It is, in essence, the original and the starting point from which all bronzes were made.”[11]

William Thorsell, Director of the Royal Ontario Museum, praised foundry plasters as fascinating witnesses of the creative process:

> “Foundry plasters are the last artifacts in the process of making bronzes and often show evidence of their role in this muscular, earthy process in interesting ways. You can like them or hate them for that.”[12]

The harsh critique by Sarah Milroy, that ..

> “In plaster cast after plaster cast, the forms are blunted and abraded, sometimes as if dipped in a coating which has congealed over their

9 Rodin: Truly a Bust, by Sarah Milroy, Toronto Globe and Mail, Saturday, 22 Sept. 2001, Page R15.
10 Symposium speech by Dr David Schaff; see also report by Dr David Schaff: Notes on Authentication of Rodin collection for the MacLaren Art Centre, 18 June 2001.
11 Unpublished letter by Mr William Moore to Toronto Globe and Mail, 25 Sept. 2001. A copy of this letter was sent to me on 23 Oct. 2001.
12 Letter by William Thorsell, Director R.O.M., to Toronto Globe and Mail, 12 Nov. 2001.

> surfaces, leaving the shapes generalized -- which indeed may be the case, depending on what, precisely, the casts were made for. Some of them are scratched and dinged or badly softened."[13]

was countered by Moore with the following argument:

> "Unwilling, perhaps unable, to cite a single example, she attacks the fidelity of the plasters and attributes coverings and damages which, when they do exist as secondary features, document the age and history and do not fundamentally compromise the integrity of their forms. There are no "deeply distressed" plasters in this exhibition. Of the fifty-four plasters in the exhibition, only five are impaired to any significant degree. (...) The plasters are not blunted and abraded nor badly softened. How exactly does she know? They are encased in plexiglass."[14]

At no point in time during the entire bitter controversy, which was extensively covered by the Toronto Globe And Mail, The Toronto Star and other major newspapers from July till at least November 2001[15], none of the parties materially involved (the MacLaren Art Center, the R.O.M., the Gruppo Mondiale Est, the Musée Rodin), disputing on the true value of a donation that had been announced to be worth 40 million Can$[16], ever took the initiative to try and document, specify or quantify the alleged damage caused by duplication and mollification processes for single plasters by means of detailed photography, precision measurements or laboratory

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13 Rodin – Truly A Bust, by Sarah Milroy, Toronto Globe and Mail, 22 Sept. 2001.
14 Unpublished letter by Mr William Moore to Toronto Globe and Mail, 25 Sept. 2001. A copy of this letter was sent to me on 23 Oct. 2001.
15 For my own documentation, I created a small electronic press archive.
16 $40 Million Rodin Collection Acquired By Northern Ontario Museum, Arts Business Exchange, April 2001; $40 Million Donation of Rodin Sculptures Kicks Off ArtCity in Barrie, Canada NewsWire, March 2001.

analysis - a laxity quite unthinkable in case of damages to cars, buildings or industrial equipment.

Given the fact that neither before nor during the Symposium, objective and reliable information on age, physical quality, provenance and status of the plasters was available to exhibition visitors, art critics and Symposium speakers, any debate on the actual quality of the resulting bronze casts had to remain vague and subjective as well. The only point of critique based on direct visual comparison of related sculptures was put forward by Sarah Milroy:

> "The two 1999-2000 castings of The Age of Bronze made by the Gruppo Mondiale, for example, don't show the sculptor to best advantage. They seem strikingly generalized compared to the earlier Edmonton Art Gallery version beside which they stand. The wrists are thicker and less defined, ribs have melted away, fingers are swollen, the musculature seems less closely observed. As one would feel looking at photographs of photographs, one senses the ever so subtle loss of texture and detail."[17]

Please note that even in this specific contrasting, readers and potential visitors were requested to rely on the "feel" and "sense" of the art critic; for the Symposium speakers invited from all over America and Europe, there was no opportunity to check the validity of this critique before committing themselves as participants in this event.

17 Rodin – Truly A Bust, by Sarah Milroy, Toronto Globe and Mail, 22 Sept. 2001.

1.4 “A bloated and disfigured monster”: How to compare similar-looking sculptures?

In her newspaper article "Rodin: Truly a bust" Sarah Milroy also described the monumental bronze cast of Rodin's ‘Thinker’, positioned in the entrance hall of the Royal Ontario Museum, as "a bloated and disfigured monster of a thing".[18]
On the other hand, Washington Post’s chief art critic Blake Gopnik claimed:

> “The Musée Rodin's complaints have almost nothing to do with artistic issues; they are about who gets to regulate the flow of money and power through the art world. In the Canadian controversy, the only question worth an art lover's time is whether the Barrie sculptures have the same effect on a viewer that versions approved by Rodin have. The answer seems to be that they do.”[19]

Aside from the question, if and how an object made by the artist himself is fundamentally different from any later - even a most successful - replicate, with regard to the casts displayed in Toronto the practical question posed itself, **how** the proportions and surface qualities of the large ‘Thinker’ cast repudiated so strongly by Sarah Milroy could be compared at all to the appearance of other, officially recognised ‘Thinker’ examples in an exact and objective way. In other words, what methods an impartial observer would have at his disposal to verify the opposing appraisals disseminated so vehemently by defenders and critics of the Toronto works, by checking their morphological fidelity to accepted reference examples?

Already during the preparation of my comparative slideshow I had noticed that only few catalogue photos were appropriate to inspect pairs of similar Rodin

18 Rodin – Truly A Bust, by Sarah Milroy, Toronto Globe and Mail, 22 Sept. 2001.

sculptures from identical perspectives. Moreover, I found that for many works no reliable dimension figures were given. Especially in the case of Rodin and his contemporaries, dimensions are highly significant in determining authenticity. A bronze cast derived from a mould in turn made after an existing metal sculpture necessarily is smaller than the original work, due to the shrinking of the cooling metal. Bronze sculptures manufactured by means of such a *moulage* technique are considered inauthentic.[20] On another scale, plasters that have been damaged at the foundry, or were duplicated from first-generation plasters evince slightly different dimensions – which could be measured with precision instruments. Only after documenting such differences for single plasters, it would make sense to discuss if these deviations "fundamentally compromise the integrity of their forms", or not.

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19 Blake Gopnik, What's the Rodin fuss really about?, Money, The Toronto Globe and Mail, New for the Week of September 3, 2001. Quoted at http://desgriffin.myevisionlink.com/New_September3.html.

20 For a discussion of this practice, see Albert Elsen and others, A Statement on Standards for Sculptural Reproduction and Preventive Measures to Combat Unethical Casting in Bronze Approved by the CAA Board of Directors, April 27, 1974, Endorsed by the Association of Art Museum Directors and the Art Dealers Association of America.

2 First steps

2.1 The Thinker project

2.1.1 Insufficient information on a famous sculpture

During the first weeks of the year 2002, a discussion with Dr Schaff developed on the morphological qualities of the monumental 'Thinker' plaster in the Toronto exhibition: the model for the criticised bronze cast in the entrance hall. To allow for a direct comparison, I scanned some catalogue photo[21] and emailed them to Philadelphia. According to Dr Schaff, the Toronto plaster had evident weaknesses; another monumental 'Thinker' plaster, a foundry plaster that had been used by the Sayegh Gallery in Paris for an announced posthumous edition of 25 colossal bronze casts, with the official support of the French Government and the Musée Rodin[22], manifested serious flaws as well.

> "My comment about the MacLaren plaster of the Large Thinker takes into account various details: the face has been re-cut and is "doughy." It is simply not well defined - and Gary[23] made changes in the bronze to correct these weaknesses. As Mary[24] will also tell you, in person the plaster shows various repairs - most of the right side of the base has been retouched, section cuts (not seams, but the joins from having been sawed apart, more than once) are obvious - and the surface has generally been "refreshed" - there is a recent

21 Rodin, Plasters & Bronzes, Robert Gordon Private Editions, for Gruppo Mondiale Est, 1999, with text by Dr Schaff and photos by Mario Carrieri; Monique Laurent, Le Penseur, published by the Sayegh Gallery, Paris, 1990, with photos by Roland Dreyfus.

22 See the book by Monique Laurent, Le Penseur, published by the Sayegh Gallery, Paris, 1990, p. 8ff. As a former Senior Curator at the Musée Rodin, Laurent lent her authority to an essay praising the quality of the plaster acquired by Sayegh. The Musée Rodin itself confirmed the morphological fidelity of the Sayegh Plaster to the Meudon example (cat. Nr. S 161) in a letter of 18 Oct. 1998, basing its judgement on photos. The exhibition and sale of a bronze cast from this posthumous edition at the Shanghai Art Fair, 2–8 Nov. 2000, received a positive comment by the French Fonsulate in Shanghai, at that time published at www.consulfrance-shanghai.org/archives/actualites/content112000.html.

23 Gary Snell, Director of the Gruppo Mondiale Est.

wash of white plaster over the more grey original elements. It is very likely that this is a plaster from Rodin's lifetime, but this item has had a hard life, in my opinion. You are right: it is generalized and lacks the life of the 73 cms. version, which also is in rough shape in certain areas.

Your images from Sayegh just came through: part of it is very well defined and part rather odd. There seem to be plenty of repairs. Also, the jowls are very fat and vague (I am not convinced they are original), the left hand soft and not detailed while the right is very crisp and full. Why is the left hand larger or is this the photography? I do not like the right shoulder and biceps - they seem either reworked or inaccurate. They do not have the tautness of Rodin's anatomy - but then we must always keep in mind that this is an enlargement, in large part mechanical. Here Snell's example may be more true to earlier forms. The legs are quite convincing in their musculature. These are the best sections - or they best fit my sense of Rodin's modeling.(...). It's powerful but abstract in sections - it should be compared to a lifetime bronze, either at the Pantheon or elsewhere."[25]

In my answer to Dr Schaff of 11 Jan. 2002 I summarized:

"So we may conclude that the Sayegh plaster:

- is a foundry plaster
- is detailed and crisp in some parts
- has a lacquer coating (gomme lacque)
- has been used
- shows obvious damage
- has been repaired
- has probably been retouched or reworked in some parts
- in some parts may be inaccurate, vague or fat or soft
- may be even more modern than the (G.M.E.) example"[26]

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24 Mary Reid, Curator of the MacLaren Art Center.
25 From a letter from Dr David Schaff to the author, 10 Jan. 2002
26 Email by the author to Dr David Schaff, 11 Jan 2001.

Since both plasters seemed to fit in to the same categorie, only an exact comparison would be able to determine which item actually corresponded to the 'Thinker' plaster kept in Meudon - or other plasters of unquestioned provenance - with more fidelity.

Musée d´art moderne et contemporain, Strasbourg (Photo: Aug. 2002).

Musée des Beaux-Arts de Béziers, 72 cm version (Photo: C. Gourmanel).

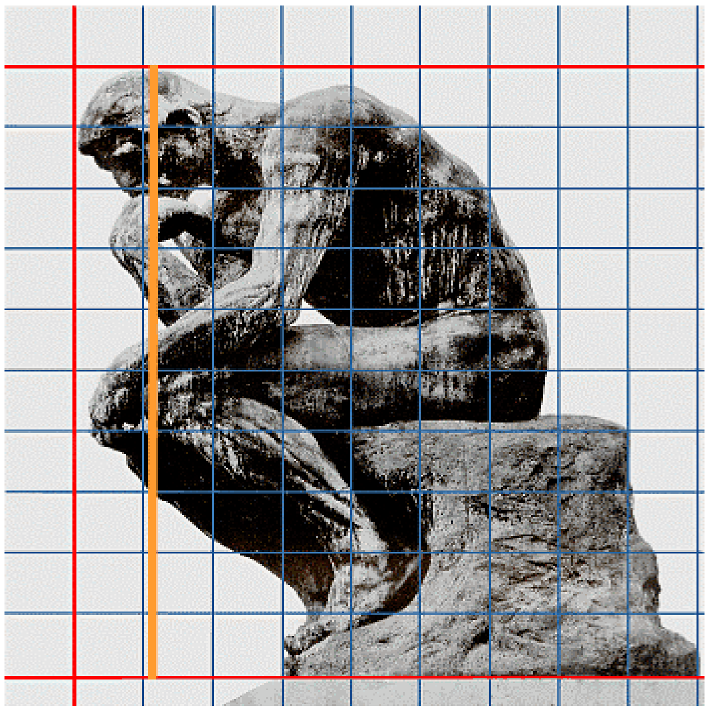
National Museum Poznan (museum file).

Sayegh Gallery (Photo: Roland Dreyfus).

2.1.2 Height, Width and Depth

To get an overview of all other relevant monumental 'Thinker' plasters, I started collecting extra information from catalogues and by corresponding with museum curators. I published the results on a separate website created for this purpose: www.penseur.org. This was the beginning of the Thinker Project.

In some cases conventional dimension figures for Height, Width and Depth given in catalogues and museum files were erroneous [27]. Not even the figures for Height, which can be measured unambiguously by measuring the distance between the highest point and an horizontal bottom plane, were always correct.



The Philadelphia‚Thinker'. Sculpture photo: Murray Weisshics by the authoris dialogue snz-Institutect relevance to the subject of this paper: has been expanding.

Moreover, while checking the bronze casts as well, I discovered that the mathematical relationships between Height, Width and Length were significantly different for casts presenting the same subject. The Cleveland 'Thinker', for example, is listed by Athena Spear with H x W x D =72" x 38¾" x 56"[28] or 182.9 cm x 98.4 cm

27 For example, in Feb. 2002, after our first meeting in Munich, the curator of the Polish National Museum checked the height of the Poznan 'Thinker' plaster and determined that this was ca. 183,5 cm high instead of 193 cm, as indicated in the museum files.

28 Cast by Alexis Rudier, gift of Ralph King, 1917. See Athena Tacha Spear, Rodin Sculpture in the Cleveland Museum of Art, 1967, Cleveland Museum of Art, Ohio, p. 96.

x 142.2 cm.[29] The dimensions of the Spreckels cast are given with 78" x 51" x 52¾" = 198 x 129.5 cm x 133.9 cm.[30] The Philadelphia cast would be 79" x 51¼" x 55¼".[31] First of all, we are confronted with seriously deviating Height figures for the Cleveland cast - corresponding to the size of the plasters kept in Meudon and other European Collections - on the one hand, and the San Francisco and Philadelphia casts, that are claimed to be ca. 16-18 cm larger.[32] Moreover, these figures indicate that the San Francisco and Philadelphia casts would be nearly as wide as deep and Height would be appr. 60% larger than Depth and Width. The Cleveland 'Thinker', on the contrary, would be much higher and deeper than it is wide.

One of the causes of this phenomenon - apart from actual differences in shape or unprecise measurements - lies in the fact that among museum professionals no uniform and binding code for determining Width and Depth has been agreed upon. For any object that does not have the simple shape of a metric cube or a perfect sphere, the selection of reference points on the surface of the sculpture for defining these parameters is arbitrary and logically influences the resulting values.

For an irregular shape like Rodin's 'Thinker', one can choose an infinite number of different point pairs to define the Length and the Width dimensions, even when measuring only at floor level. By rotating the sculpture along its vertical axes, still other point pairs present themselves as suitable alternatives. The same goes for Width.

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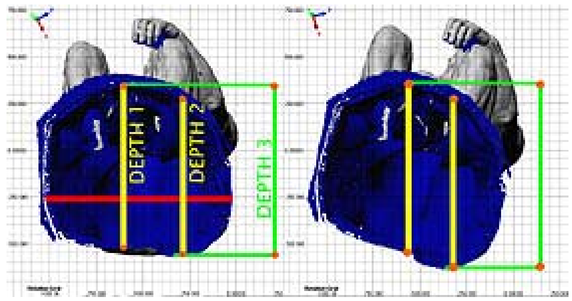
29 Cleveland Museum Website at www.clevelandart.org.

30 Jacques de Caso, Patricia B. Sanders, Rodin's sculpture: a critical study of the Spreckels Collection, California Palace of the Legion of Honor. 1977, Fine Arts Museums of San Francisco, p. 131.

31 John Tancock, The Sculpture of August Rodin - The Collection of the Rodin Museum, Philadelphia, 1976, Philadelphia Museum of Art, 1989, p. 111.

32 In his 1939 book on Auguste Rodin, Phaidon Editions, Paris/George Allen & Unwin, London, 1939.Georges Grappe, Curator of the Musée Rodin, wrote. "Penseur, executé en taille demi-nature vers 1879, pour encaster dans La Porte, fut exposé dans sa hauteur de deux mètres, en 1900, au Pavillon de l´Alma que Rodin s´était fait construire pour y grouper son peuple de chefs-d´oeuvre."
In fact, the 'Thinker' enlargement was only ready by Sept. 1903; in the Joconde Database, I could find no reference to over-sized 200 cm 'Thinker' plasters.

And since there is no valid convention that Width and Depth should only be measured at floor level, any museum Curator or scholar is free to select other points on the surface on the sculpture above floor level, that may seem appropriate to him/her, but cannot be reconstructed by the readers of his/her catalogue, since the position of the selected points is not documented along with the dimension figures. For this reason, the Width and Depth figures given in catalogues have no objective, scientific value, even if they would have been measured with submillimetre precision. Only if the spatial co-ordinates of the selected points have been objectively fixed it makes sense to refer to Width and Depth for purposes of comparative research.



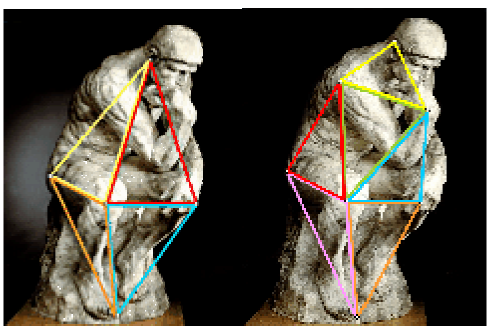
Dr Alain Beausire, Paris, who had supervised the Archive of the Musée Rodin for over 20 years, commented on the photos and official dimension figures of large 'Thinker' plasters I had sent him in December 2003 as follows:

> "En 1er lieu, mon opinion s'exprime uniquement dans la limite des informations mises à ma disposition, notamment les dimensions et les photographies. Celles-ci montrent les plâtres dans des conditions différentes d'angles de vues, d'éclairage, de détails…
>
> Les dimensions données ne sont pas contrôlables :
>
> 1. Sachant que si dix personnes, aussi compétentes soient-elles, mesurent le même objet, il y aura dix résultats différents.
>
> 2. Pour que ce paramètre soit pris en compte avec sérieux, il faudrait qu'une seule et même personne officie et toujours dans les mêmes conditions avec les mêmes instruments.
>
> 3. Dans ce cas particulier du grand Penseur en plâtre, certains comportent une plaque protectrice en bois sous la base ; d'une part elle

peut avoir une épaisseur différente, d'autre part, étant parfois recouverte de plâtre, elle a été incluse ou non dans la mesure de la hauteur.

4. Il est probable que les coupes des bases ne soient pas exactement les mêmes, ce qui rend la comparaison, pourtant courante mais pour moi non révélatrice, des profils au sol de la base inadéquate. "[33]

This comment by an outstanding Rodin specialist confirms the need for more objective techniques of measurement in the museum field. The same concern had been expressed by Prof. Jacques de Caso during our meeting in Munich on 11 Jan. 2003; de Caso strongly supported my plans to develop such methods and to document similar-looking sculptures in different collections, among others. By March 2002 I had published a simple diagram at www.penseur.org to illustrate my approach. It shows a primitive geometric model describing the outer shape of a sculpture. The model consists of a set of surface co-ordinates, connected to build triangles. The more spatial co-ordinates are taken into account, the smaller the triangles will be. By increasing the number of vertices and triangles, the resulting network will describe the surface of the sculpture with growing precision.



Defining co-ordinates and proportions
Photos Sayegh ,Thinker': R. Dreyfus.

2.2 First outline of The Rodin Virtual Sculpture Project

Already in April 2001, I had created stereographic images of 'The Age of Bronze' at the Haags Gemeentmuseum in Den Haag and published them online. One of the friends accompanying my wife and me to Toronto was a specialist for interactive presentation of 3D content over the Internet. Still in Toronto, we discussed the possibility of creating 3D models of sculptures by means of 3D photogrammetry and to use these data, for example, to compare the criticised objects at the R.O.M. to similar sculptures in other collections - expanding the idea of the comparative slide show to include the third dimension. We also discussed the possibility of presenting Rodin works as compressed digital models over the Internet. This conception was the starting point of the Rodin Virtual Sculpture Project. On 9 Dec. 2001, an exposé on possible applications and suitable methods was submitted to Bernard Barryte at the Cantor Center for Visual Arts at Stanford University as a proposed Symposium contribution. The same exposé was sent out to the Bavarian Ministry of Science, Art and Research, to the Neue Pinakothek and the Glyptothek museums in Munich, and to the MacLaren Art Center. MacLaren staff welcomed my idea to document their plaster collection, but insisted on finding Canadian sponsors for this trip; since this proved to be difficult, a second visit to Toronto was postponed time and time again.

The other institutions addressed showed no active interest; the Cantor Center preferred more conventional contributions to its congress on "New Studies on Rodin", that was to take place on 4-5 Oct. 2002. To get ahead, I decided to develop and implement my ideas on my own account. In January 2002, I met with Piotr Michalowski, Curator of the National Museum in Poznan, Poland, to discuss my ideas and plan 3D measurements of the monumental ‘Thinker’ plaster in Poland, together with the informal support team that started to develop around this concept: students of French and German Literature, Intercultural Communication, Art History, Information Technologies, young photographers and media specialists.

33 Comment on the Poznan ‘Thinker’ by Alain Beausire, sent to the author by email on 10 March 2004.

3 Methodological context

3.1 History of Photogrammetry and non-contact 3D measurement techniques

The principle of surface documentation by means of geometric co-ordinates derived from photographs was discovered and applied for the first time in 1849 by Laussedat, only ten years after the invention of photography. Laussedat designed a photothedolite and used triangulation methods to create maps. Between 1849 and 1933, photogrammetry has been developed further by Nadar, Adams, Scheimpflug, Deville, Pulfrich, Fourcade, von Orel, Nistri, Zeiss, Hugershoff, Bauersfeld, Poivilliers, Wild, von Gruber, Lacmann, Ferber and others. The term "Digital Photogrammetry" first emerged at the 1984 ISPRS Congress in Rio de Janeiro; in 1988, Gugan and Dowman defined real-time scanning of 3D models as an essential feature of digital photogrammetric stereoplotting systems.[34]

The development of digital 3D scanning devices in the 1980's and 90's today enables us to measure the spatial co-ordinates of thousands of points within seconds, thereby producing a highly accurate virtual 3D representation of the object. Especially in Germany, coded light / phase shift / fringe projection methods were designed as an alternative to laser scanning (Breuckmann, Steinbichler, Wolf, Massen and others). In October 1994, an International Conference on Non-destructive Research on Art and Culture Heritage Goods was held in Berlin.[35]

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34 See Lectures on Photogrammetry, by Dr C.P. Lo , Department of Geography, University of Georgia, currently availabe at http://www.ggy.uga.edu/courses/geog4430_chpanglo/lecture.html.

35 See for example: Duwe, H.-P.; Gründer, K.-P.: “Dreidimensionales Vermessen von Oberflächen mit Video-Kamera, strukturiertem Licht und Bildauswertung“, 4. Internationale Konferenz Zerstörungsfreie Untersuchungen an Kunst- und Kulturgütern, Berlin 3–7 Oktober 1994, DGZfP Berichtsband 45, Teil 1, S. 92–101.

3.2 The Digital Michelangelo Project

Since 1992, Professor Marc Levoy and his team at Stanford University, California have been exploring methods of creating virtual geometric models of sculptures by means of laser scanning. In 1996, the Stanford team demonstrated the possibility of building a 3D fax machine: a little Buddha statuette was captured by 3D laser scanning, the resulting data were digitally transmitted to another laboratory, where a replica of the scanned object was produced. At that time, the National Research Council of Canada regularly employed 3D data acquisition to scan cultural artefacts[36].

. In 1989/99, Professor Levoy and his staff spent a year in Italy, to scan ten large Michelangelo sculptures, 1,163 fragments of an the Forma Urbis Romae, a marble map of ancient Rome and two buildings. The Digital Michelangelo Project website[37] currently indicates, Levoy had a budget of 2 million US $ available and a 32-person staff to create and evaluate these 3D data. At that time, nobody had digitized a large statue with enough accuracy to serve as a primary source of scientific work and nobody had tried to digitize a large and coherent collection of statuary, according to this presentation. As the device used for data capturing, Levoy's online report by the end of 2001 presented the so-called Stanford Large Statue Scanner custom-built by Cyberware of Monterey, California: a laser scanner on a a 3-foot horizontal arm vertically translating on an 8-foot metal truss mounted on a rolling platform. To reduce deflection of the gantry, motions are balanced by a lead counterweight sliding inside the horizontal arm.[38]

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36 See Digital Michelangelo Project website: www.graphics.stanford.edu/projects/mich/
37 As mentioned above: www.graphics.stanford.edu/projects/mich/.
38 Source: www.graphics.stanford.edu/projects/mich/mgantry-in-lab/mgantry-in-lab.html.

4 Meeting the challenge: the Digital Sculpture Project

4.1 The specific qualities of my project

For me, the challenge was not to imitate Levoy's project, but instead develop and apply a method for creating highly accurate 3D scans of both large and small sculptures within narrow time windows in improvised non-laboratory environments, with a much smaller team and without any institutional budget or facilities. After a difficult start, all these demands could be met: From September 2002 (first 'Thinker' scan) till November 2004, I traveled to 12 different museums in Germany, France, Italy, Switzerland and Poland and produced 3D scans and (stereo-) photos of more than 30 sculptures by Rodin and his contemporaries during 18 visits, mostly together with a technician and one or two photo/video assistants.

Transport of team and equipment by esate car plus 470 liter roof box.

As a rule, we transported all equipment with two estate cars; for our trip to the South of France, I installed a 470 liter roof box on my Volkswagen Passat, so that we could transport three persons and all equipment by road, while our technician traveled by plane. For scanning small to medium size sculptures with a Faro arm, I built a demountable wooden table, put up on metal IKEA legs fixed on heavy iron discs - cushioned with cork - from my Manfrotto photo studio equipment. On this steady, yet transportable scanning platform we would mount the scanner arm.

We mostly worked on Mondays or Tuesdays, when the museums were closed to the public; in a few cases, we were allowed to work in early morning hours, late at night or in an extra room, so that we did not disturb the public.

Faro Arm on demountable scanning platform.

In contrast to other 3D sculpture scanning tasks mostly commissioned within the framework of publicly financed conservation/restauration projects or university /polytechnic research programmes[39], all costs were financed from my own savings. The result of this private passion is also relevant for publicly financed undertakings: Evidently, limited budgets can suffice to accomplish state-of-the-art 3D scans, once the most efficient workflow has been determined. Exactly this was the point I had to focus on, resulting

39 Some recent examples of such projects by Germany-based academic and corporate teams:

- Mariensäule Salzburg, scanned with Breuckmann equipment
- Statues on Karlsbrücke Prague, scanned with GOM equipment
- Digitizing of the ancient bronze sculpture of Apoxyomenos with GOM equipment.
- Marburger Dom, outdoor saint figures, scanned with Minolta.
- 3D recording and visualization of the Cenotaph of Maximilian I. in the Innsbruck Hofkirche, using GOM and Mensi scanners, by i3mainz Institute.
- Plaster sculptures made by Paul Klee analysed by Prof. Friedrich Klein and Institut für Angewandte Forschung in Aalen, using a 3D CT Scanner.
- Celtic wooden sculptures of Fellbach-Schmiden, counting the number of year rings by means of CT scanning, by Prof. Friedrich Klein, Aalen as well.

in some insights about workflow productivity that may be beneficial for other cultural initiatives as well.[40]

As far as I am informed, my project is also unique in that sense, that for the first time attention was given to documenting pairs of similar sculptures located in different places, adressing the possibility of exact morphological comparison without need to transport the fragile works. By now, six pairs/groups have been scanned, enabling an evaluation of similarities and differences in Rodin's work between

- early and later examples
- variations of the same basic subject
- plaster, terra-cotta and bronze examples
- original size works and monumental enlargements

Since I concentrated on works of well-documented provenance and accepted museum exhibition quality, the virtual collection presents a suitable reference for testing items of uncertain origin or quality – highly relevant for an art market flooded with fakes[41].

To demonstrate the feasibilty of an exact morphological comparison between two identical-looking sculptures by means of industrial 3D inspection software, mostly used in the automotive engineering field, I created a 3D difference model during a work session with Dr Hans-Peter Duwe in Lindau on 15 Dec. 2003, visualising and quantifying the exact morphological distinctions between two monumental 'Thinker' plasters in Strasbourg and Poznan respectively. Screenshots extracted from this 3D model represent colour-coded difference maps. (see Chapter 4.5.6).

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40 In the many publications by the i3mainz-Institute in Mainz, for example, I found only one report on the use of measurement arms; the combination with a scanner head has not been tested, so that in Germany, the workflow advantages of this system has hardly been investigated and published outside the automotive and engineering field. See Chapter 4.5.3 and Heinz, G.: Comparison of Different Methods for Sculpture Recording, Hakodate, 1998.

41 "Even so, two out of three pieces of bronze sculpture I see today are problematic," Jerome Le Blay, senior specialist at Christie's auction house, told United Press International. "It makes for huge price differences depending on the piece." Quoted in: Frederick M. Winship, The Art World: Fake bronzes flood market, released by United Press and published by www.museum-security.org on 16 August 2002.

4.2 Some applications for art-historical analysis

The advantages and applications of 3D survey and inspection technology for art-historical analysis can be summarised as follows; this list is not exhaustive and new applications may develop over time.

Free selection of point of view:

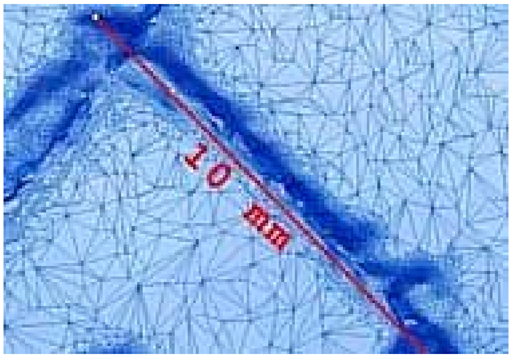
A main advantage of topometric data capturing is that one can view the virtual model from all sides at a computer screen. When the data are sufficiently compressed, the 3D model can even be made accessible over the internet, with interactive viewing and zooming. Different kinds of compression software and viewers are already available.

Comparing dimensions and proportions of sculptures:

One of the most interesting applications of geometrical models consists in the possibility to compare sculptures located in different collections with each other in all details, without need to transport the items. With special inspection software, even the tiniest differences between two sculptures can be quantified and visualized.

Qualitative comparison of sculptures:

High-resolution models allow to document and study surface characteristics like nicks, scratches, fissures, fractures, plaster bubbles, etc. By comparing plaster objects to undamaged reference items one could answer the question, for example, if the much-discussed Toronto plasters actually lack profile and detail because of wear and tear during foundry processes. By an exact morphological comparison, it would also be possible to



High-resolution scan with GOM system.

discern a duplicate from its original model, for example, by measuring the loss of sharpness and definition. In combination with other methods (see below) age, constructional details and the nature of materials used can be analysed.

Original or fake?

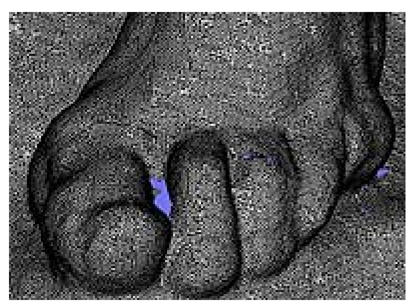
By documenting morphological details "finger prints" of sculptures can be made, that can help to identify single items unambiguously, e.g. for insurance purposes or to protect the artist or the owner of the original against unauthorised reproduction. It would also be possible to detect fakes, that look identical to authentic sculptures when viewed with the bare eye or measured by conventional methods but show significant differences when inspected more exactly by means of 3D data.

Documentation and conservation of the present state:

By means of 3D measurements the present state of fragile or perishable objects can be preserved in digital media, that can be consulted for later repair or reconstruction in case of damage. It is also possible to document the present condition of an object before a planned restauration. By scanning the object a second time, a before/after analysis can be performed. Scanning outdoor sculptures at fixed time intervals allows for long time research of erosion effects.[42]

Detecting/displaying falsifying restaurations:

A detailed morphological comparison of two examples of the same subject can eventually show up restaurations that have caused involuntary falsifications of the original shape.[43]



Foot of the Strasbourg ‚Thinker' showing rudimentary small toes.

Reconstructing the original model:

3D analysis can also demonstrate purely contingent characteristics of an example, caused by unprecise

42 Example: scanning of Celtic stone crosses by David Hampton with Surphaser equipment in Edinburgh, Summer 2002.

43 My comparison of the Strasbourg and Poznan 'Thinker' plasters has demonstrated such falsifying repairs of the left foot (Strasbourg) and the left-hand fingers (Poznan) respectively.

fitting of mould forms or irregular flowing, drying or shrinking of the material used, or damages. By comparing several examples, such individual, accidental characteristics can be filtered out, so that the underlying original shape can be reconstructed as an ideal form, even when the physical model has been lost and none of the copies is flawless.

- **Documenting the shrinking process occurred during casting:**

Still another application can be found in the geometrical comparison of a plaster cast with a bronze cast created from this plaster shape. An exact morphological analysis allows for determining the exact quantity of metal shrinking and can point out formal deformations due to irregular shrinking or unprofessional chiseling.

- **Comparing the results of competing casting methods:**

It would be possible to compare the results of lost wax and sand casting - two casting methods that already competed during Rodin's life-time.

- **Visualising deformations due to enlargement and reduction:**

From ca. 1900 on, Rodin had his collaborator Henri Lebossé produce a series of enlargements and reductions, in order to satisfy the differentiated needs of collectors and institutions.[44] These translations were made by means of a Collas Machine and then corrected under the personal supervision of the artist. Since virtual models can be variably scaled, it would be possible to determine the exact effect of this process with regard to morphological fidelity.

- **Comparing initial model and final execution:**

By the same methods, it is possible to compare the first draft of a sculpture with the later, final execution and visualise the adaptions and corrections made by the sculptor in their exact quantitative amount.

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44 See Albert Elsen, Rodin’s ‘Perfect Collaborator’, Henri Lebossé, in: Rodin Rediscovered, National Gallery of Art, Washington, 1981

Comparing the marble-cutting by different *praticiens*:

Rodin had his marble sculptures executed by talented young sculptors, who sometimes left their own impress of style in the final work. For this reason, Rodin was not too happy with the marble ‘Bust of Mme Vicuna’, cut by the talented Jean Escoula:

> “Exquisitely charming as it is, the sculptor does not regard is as a fully satisfactory reproduction of his model, because it bears too much the impress of the character of the superior marblecutter who executed it. Rodin understands the fine fact, that just in proportion that a marble workman excels in his trade does he unconciously give his work his own interpretation of the model which he copies. And this in spite of the most exacting means of mechanical measurement that he may employ.”[45]

By comparing different marbles executed by different *praticiens*, it would be possible to determine precisely how much of their own "handwriting" these praticiens realised in their respective executions.

4.3 Documentation grid based on text sources, photography and 3D data capturing; complementary methods

Over the past three years, a standard grid for documenting single sculptures developed, based on interviews, correspondence, archive and catalogue research, as well as photography and 3D data acquisition/analysis:

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45 Truman Bartlett, “Auguste Rodin, sculptor”, in Albert E. Elsen, “Auguste Rodin: Readings on his Life and Work”, Englewood Cliffs, N.J., 1984, p. 84 (reprinted from the American Architect and Building News, XXV, Nos. 682–703, 19 Jan–15 June 1889. Comment quoted by John Tancock, p. 36; see also Athena Tacha Spear, p. 70.

- To focus the questions a morphological documentation might answer, **art-historical research** about provenance and significance of the work must be accomplished.
- High-resolution **colour photography** delivers detailed "flat" records of the work and of details of special interest.
- **Stereo photography** combines pictures taken from slightly different angles and allows for spatial viewing as anaglyph images or slide pairs.
- **3D co-ordinates** of points on the surface of the object are measured with topometric equipment, using different scanners according to the special shape and surface qualities of the sculpture. If necessary, two or more scanning methods can be combined.
- The session is **videotaped** in order to create a meta-documentation for later reference.
- Through co-operation with **partner laboratories** ultrasound and X-ray tomography scanning can be arranged for, to measure relative densities within an object (consistency analysis, exploring inner cavities, locating metal armaments in plaster sculptures).
- On a powerful workstation with special **3D software**, a mesh file can be created representing the sculpture as a virtual model.
- By **comparing** two virtual models made of similar sculptures, even the smallest differences can be quantified and visualised.

If necessary, other advanced methods of research can be included as well, like X-Ray Spectometry, X-Ray Radiography, Electronic Microscopy, Gas-Chromatography, X-Ray Diffractometry, Thermoluminescence, etc., as currently developed and applied for analysis of art objects by the French C2RMF Institute in Paris/Versailles, the Rathgen Research Laboratory in Berlin, and other institutions.

4.4 Equipment testing

Units for accuracy, point distance: 1 mm = 1,000 micrometer = 1,000 µ = 1,000 micron **Dimensions**: z-axis runs from lens to object **Vocabulary:** patch = range map = point cloud created by a single scan **Abbreviation**: F.O.V. = Field-Of-View

By the end of 2001, four methods of 3D data capturing seemed relevant to me:

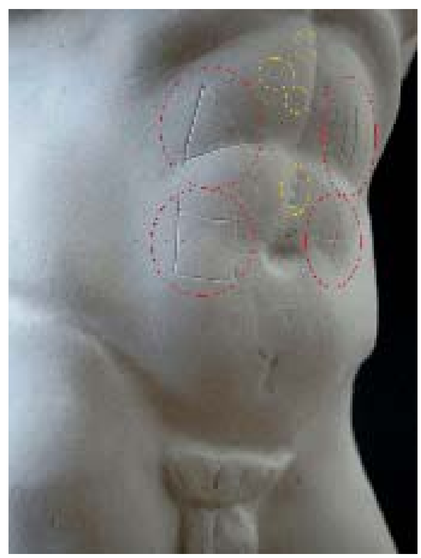
- **Photogrammetry:** based on a series of photos that define the shape of the object.
- **Laser triangulation:** calculating the z-distance (depth) of a point matrix from the reflection of a laser beam, projected by a rotating mirror.
- **Single-LineOf-Sight Phase shift:** calculating distances from the phase shift of a light beam. To determine absolute distance, various wavelengths are needed.
- **Fringe projection/structured light:** stripe patterns are projected on the object and recorded by a digital camera.

All methods have their specific advantages and weak points, depending on the goals to be reached. Although my exposé of December 2001 still was based on photogrammetry, as an alternative to the costly custom-built Cyberware scanner used in the Digital Michelangelo Project, I soon realised that photogrammetry would not suffice to create 3D models in real-time[46], and that not all equipment capturing complete surfaces would cost the price of the Stanford Large Statue Scanner.

46 For a comparison of photogrammetry and 3D scanning in the cultural heritage field, see: Böhler, W.; Marbs, A.: 3D Scanning and Photogrammetry for Heritage Recording: A Comparison – Proceedings of the 12th International Conference on Geoinformatics, June 2004, pp. 291–298, Gävle, Sweden, 2004. Böhler and Marbs relate to their experience with the GOM Atos system. When needed, GOM and Breuckmann employ photogrammetry as additional methods. The disadvantage for sculpture scanning is the use of reference marks: for scanning fragile plaster items, I could not use paper marks that might stick to the plaster.
For an advanced discussion of the use of photogrammetry for capturing sculptures in 3D, see Kwan-Yee K. Wong and Roberto Cipolla, Reconstruction of sculpture from its profiles with unknown camera positions, draft version for IEEE TRANSACTIONS ON IMAGE PROCESSING, currently available at www.cs.hku.hk/~kykwong/publications/kykwong_tip04.pdf.

In February 2002, I sent out a project description to the following companies, asking them to explain if their scanning device or service would be appropriate for my goals:

- 3DD Digital Corp., Danbury, CT
- 3DTech
- 4DI, Automation-Online, Chelmsford, MA, USA
- Chronosvision/Integrated Vision Products, Germany/Sweden
- Cyberware, Monterey, CAL, USA
- Immersion Corp.(Microscribe), San José, CAL, USA
- Kreon Technologies, Limoges, France
- Minolta 3D, Langenhagen, Germany
- Perceptron, Plymouth, MI, USA
- Polhemus FastScan, Vermont, USA
- Riegl - USA
- RSI, Oberursel, Germany
  (PhotoModeler, MicroScribe, Polhemus)
- Roland DGA Corp., Irvina, CAL, USA
- ShapeGrabber Inc., Ottawa, Canada
- Steinbichler, Traunstein, Germany
- Wolf & Beck, Wangen, Germany
-



Little plaster torso with scratches for testing scan quality.

I also collected information on:

- Hymarc, Ottawa, Canada
- ScanTech, Ringsted, Denmark
- Eyetronics, Heverlee, Belgium
- Arius 3 D, Mississauga, Ontario, Canada

In the following weeks and months, I compared the specifications of the various digitizing systems with the **special requirements of my project**:

- The system should be **portable**, since my team would have to scan on location.
- It should be able to scan **both small (10 cm high) and large (>2 m) sculptures**.
- It should have high enough **resolution and accuracy** to document finest modeling details and surface structures; this would allow me to identify cracks and nicks on plaster items or compare a bronze sculpture to the plaster model it had been cast from.
- It should function under **normal indoor light conditions** (direct sunlight excluded).
- It should be **flexible** enough to reach all areas of a complex sculpture.
- The method should be **safe** for the sculpture; there should be no need to touch the sculpture for the actual measurement; the sculpture should be moved as little as possible.
- Scanning should be so **fast** that my team would be able to scan a medium size sculpture (1 meter high) within a working day.
- Point cloud **file formats** should be compatible with industry standard software like Geomagic, RapidForm, Polyworks.
- It should be possible to **align** single range maps (scan patches) still in the museum, to check if we had captured the sculpture completely.
- The system should either be so **affordable** that I could buy the equipment, or it should be available on a rent basis.

Although many manufacturers feature sculpture scanning on their websites as a possible or even favourite application of their equipment, I had to find out that many devices would not meet the criteria of my project. Some simple examples:

- Cyberware has earned a high reputation by supplying tailor-made equipment for the Digital Michelangelo Project, but the ModelShop system limits the size of the objects that can be scanned and requires they are mounted on a moving platform.
- The Roland LPX-250 is only suitable for very small objects, that fit into a scanning box
- The Polhemus system employs a magnetic tracker, that is negatively influenced by the metal armaments within a plaster sculpture.
- Arius 3D employs a highly accurate Hymarc scanner, but the system can neither be bought nor rented.

To find out which equipment would really fit the project's needs, I organized a series of test and demonstration sessions with a selection of 3D digitizers that seemed to qualify according to producer information.

4.4.1 Konica-Minolta Vivid 900

For this test meeting in Munich on 26 Febr. 2002, I prepared some test objects made of various materials. The main features of the Vivid 900 system[47] are:

Minolta Vivid 900.

- This scanner, like its predecessor model Vivid 700, is based on the principle of laser triangulation. A laser line is swept over the object by means of a rotating galvanized mirror. The

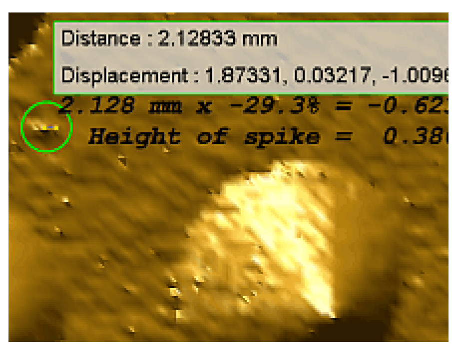
47 By Fall 2004, Konica-Minolta has introduced a new version, the VI-9i, that should have a 4x higher accuracy than the Vivid 900. Maximum accuracy is now advertised as 50 micrometer in X,Yand Z axes under our standard conditions with a TELElens at a distance of 0.6m. Source: http://www.minolta-3d.com. From this we can conclude that the Vivid 900 has a maximum x,y accuracy of 200 micrometer.

reflected laser beam is recorded by a video CCD chip covering 640 x 480 points. A 3D software package interpretes these data as a set of 3D co-ordinates (point cloud).

- The system can capture both small and large structures, in varying resolutions, featuring three different, exchangable lenses for wide, normal and tele angles.
- With one scan, the scanner captures ca. 307.000 co-ordinates in 2.5 seconds. With the telelens, a Field-Of-View (F.O.V.) as small as 111 x 84 mm can be scanned, which results in a maximum resolution of almost 6 lines/mm.

Scanning a wooden board with conical marks in my atelier during the demo meeting.

In the course of the day, we made several scans. Single range maps were aligned with software based on RapidForm. In the scan of my wife's hand, we could recognize the hand lines. The scan of our wooden test board was so precise, that we were not able to measure any errors by means of our steel rules and calipers - the traditional tools of museum staff. Over a given point-to-point distance of 60 cm, the error was less than 0.5 mm - a more precise statement was not possible, due to the lack of precision of our manual measurements.



Evaluation of Vivid 900 scans.

Still, there were some points that raised doubt with us: To obtain maximum resolution of 6 lines/mm, F.O.V. is reduced to 111 x 83 mm with focal depth at 40 mm; it seemed very time consuming build complete model by aligning such small range maps with limited depth. Moreover, I suspected the scanner, with a weight of 11 kg, would be too bulky for my goals. To scan a larger sculpture from above, the scanner has to positioned as high as 2.5 till 3 meter. Since our museum visits would involve time pressure and improvisation, I did not feel comfortable with this idea.

Despite these doubts, I stayed in touch with Minolta staff Marco Zajac and Stefanie Adolf, to exchange ideas and practical experience. Together with other companies and institutions, Minolta 3D supports the European VIHAP 3D Forum, which I joined in June 2002 as a member of the Special Interest User Group (SIUG).

4.4.2 3D Digital Corp. Model 300

After the Minolta demonstration, I looked for a scanner that would be lighter and avoid the focal depth problem. One of the companies that eagerly responded to my enquiry was 3D Digital Corp. in Connecticut, producing light, low-cost scanners.

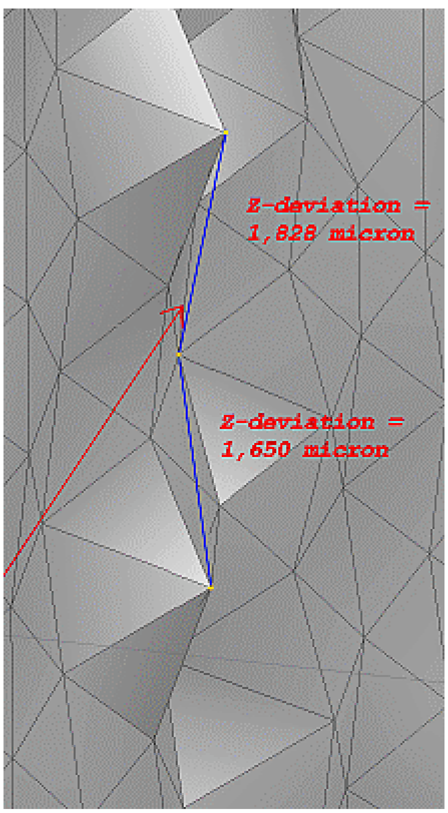
The Model 300 was demonstrated to me and my team by Paul Davison, 3D Digital Corp. representative in the UK, in my atelier on 4 April 2002. Again, we made some test scans with different pappmaché and wood objects, and were fascinated to see these irregular structures quickly appear on the screen as coloured models. Since I had planned to make a second trip to Canada in June 2002 and only little time was left to collect practical experience, investing in the 3D Digital Corp. Model 300 seemed to be a logical choice.

The 3D Digital Corp. Model 300 in my atelier.

The 3DD Model 300 is also based on the principle of laser triangulation, like the Minolta Vivid. The Sony B/W chip is slightly smaller, so that the scanner covers 512 x 500 = 256,000 points in ca. 3 seconds.

The main advantages of the system are:

- Compared to the Minolta, the 3DD system is more flexible, since the distance between object and scanner can be varied between 20 cm and 2 meter, without changing the lens.
- The Field-Of-View and the scanning resolution varies accordingly. At the minimal distance of ca. 20 cm, a resolution of 4 lines/mm can be reached, with a F.O.V. of ca. 20 x 20 cm.



Bumps > 1.6 mm on smooth surfaces.

Weighing only 2.5 kg, this highly compact equipment is very easy to handle; it can be mounted on any photo tripod, in any position. Unlike the Minolta, that has its own LCD display, display and scanner parameters of the Model 300 - like laser brightness and F.O.V. clipping - are controlled by the user´s PC or Notebook, connected to the scanner by USB cable.

Only later I realized my testing strategy had had serious shortcomings. In later test scans my friends I tried to capture smooth materials like plastic bottles, and were disappointed to see orange-skin-like, bumpy surfaces - bumps that had not attracted our attention on rough surfaces, but now jumped to the eye.

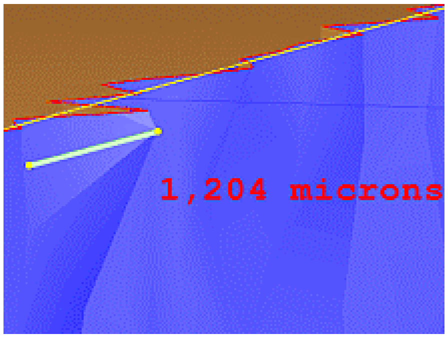
I had elaborate discussions with 3D Digital Corp. staff how to overcome this problem. By applying software filters, I was able to smooth out the bumps - only to loose the finer detail where I needed it.

3DD staff suggested the scanner we used might have a calibration problem. I had the company's technician send me a data file of the calibration block, scanned by a factory scanner. The calibration block consists of metal plates, polished by a precision manufacturer and coated with thin white lacquer to prevent reflection. With ScanSurf software, I was able now to determine the height of the bumps in the calibration file, as z-deviations from the average plane, measured in 90 cm distance.

Beethoven bust with ‚orange' skin.

I found some single bumps to be as high as 1,6 - 1,8 mm, and extensive bumps patterns with z-deviations of ±400 till ±500 micrometer. According to the scanner´s technical specifications, accuracy along the z-axis should be ±250 micrometer. Confronted with my critique, 3DD maintained that specified accuracy represented the average value of a larger sample of points.

Finally, I had to conclude that this lower-priced scanner certainly is suitable to scan simple models or surfaces that can be smoothed out and edited afterwards - like car doors -, but would not help us to document the finer details of plaster sculptures with the accuracy I had in mind.



4.4.3 Surphaser Model 25

This time, my focus was on higher resolution and accuracy. While trying to solve problems with 3D Digital Corp., I maintained communication with other companies that approached me. One of them was Basis Software in Philadelphia, that produces the Surphaser scanner.

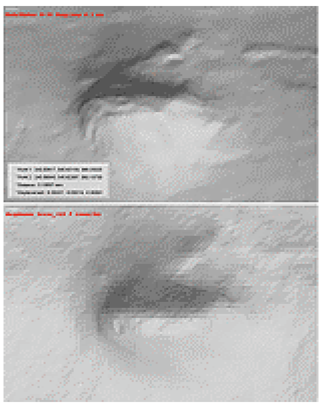
Surphaser Model 25.

The Surphase Model 25 had been developed in Russian laboratories and brought to the market by Peter Petrov, the founder and owner of Basis Software. His company had earned a name and some capital by developing "Vital LISP" CAD software. After selling off this product to Autodesk Inc., Basis Software set out to produce a laser scanner that should combine high accuracy with a large Field-of-View.

The main features of this system are:

- As a special advantage for sculpture scanning, Surphaser has a Single-Line-Of-Sight measurement system. Instead of using triangulation, the scanner sends out a single laser beam through a system of rapidly rotating lenses, thus projecting a spiral that moves from the centre to the edge of a circular Field-Of-View. The light phase of the reflected beam is compared to that of the emitted beam. This phase shift calculation allows for measurements with very high z-accuracy (z = distance between lens and object).

- Since the scanner cannot discern if the phase of the returning beam has shifted only once, or twice, or three times, additional projections are made with larger wave lengths. For every scan, four different projections are necessary [48].
- With, for example, a 22° F.O.V. resulting in a circular scanning envelope op 40 cm radius in 100 cm distance (focal depth: 90-110 cm), the system can reach an x,y resolution of 6 lines/mm equalling a point distance of ca. 170 micrometer[49], with a typical x, y accuracy of ca. ± 50 micrometer. A multiple-wavelength scan records up to 8 million points, which are saved in a "trace" file and filtered/resampled for further data processing.



Comparing ModelMaker and Surphaser scans.

I had elaborate email communication with Jim Morgenstern and Peter Petrov at Basis Software, and Mike Davies at AG Electro-Optics, the UK representative for this new system, to check if it would meet the requirements of my project.

The query was haunted by ill fate: the demo scanner at AG EO was damaged when a technician dropped it to the floor, so that a sample plaster torso I sent to England finally had to be scanned in Moscow, with a month's delay. A flight to Moscow to meet Peter Petrov for a demo session at his lab had to be cancelled, due to visa problems.

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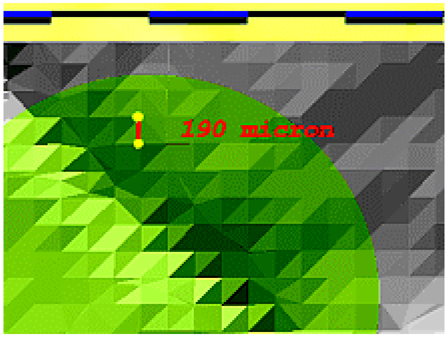
48 In Germany, phase shift 3D data capturing methods with various wavelengths (spatial heterodyne interferometry) have been researched and applied by Prof. Robert Massen, University of Applied Sciences Konstanz, and others. See also: Trautner, K. Walcher, M. Krauß, G. Leuchs, B. Bodermann, H. R. Telle, Interferometrischer 3D-Sensor zur berührungslosen Vermessung technischer Oberflächen, VDI Berichte Nr. 1572, 2000, currently available at www.kerr.physik.uni-erlangen.de/Veroeffentlichungen/InMik/BAMI-vdi-berichte_1572.pdf

49 Source: http://www.surphaser.com/products.htm#Options.
An Excel spreadsheet sent to me by Mike Davies calculating lines/mm resolution indicates an average value of only 3 lines/mm, due to the fact the scan spirals are wider apart at the edges of the F.O.V. See Appendix for details.

But the mesh file I finally received from Moscow contained a well-detailed model of the little plaster torso, clearly showing the small scratches I had made in the belly area, with an acceptable noise ratio in the smooth parts.



Evaluating the Surphaser mesh file.

On 16 May 2002, I took a plane to London to meet Mike Davies and Peter Petrov for an individual demo session at the Hilton London Stansted Airport Hotel. During two days, I had ample opportunity to see the Surphaser in action and discuss scanning strategies. This time, we scanned a small pappmaché dance figure, placed on a rotating table.

Although the concept of the phase shift scanner is very advanced, and the technical performance of the equipment seemed flawless, some important objections remained:

- Beam angle and scanning distance are factory-set. Focal depth is ca. 20% of this distance, e.g. ±10 cm in 100 cm distance. This fixed F.O.V. limits the system's flexibility. As a matter of fact, for larger sculptures I would need two different scanners: one to capture large areas with ca. 1 meter radius, another one to scan smaller areas in higher resolution.
- With a weight of appr. 5 kg, the Surphaser is much lighter than the Minolta Vivid, but still twice as heavy as the 3D Digital Corp. Model 300. Handling this weight when scanning a sculpture from above might prove a bit awkward.
- Due to the rotating lenses, the equipment produces an acoustic rumble, reminding a bit of a vacuum cleaner.

- Although data acquisation at 200,000 points/second looks fast, it can take up to four minutes to run a single scan, comprising multiple projections with varying wavelengths.
- The Surphaser demonstrated still was a prototype, the software still lacked an user-friendly interface; repairs and calibration would have to take place in Moscow.

Trying to weigh the pros and cons, I finally decided not to invest in this equipment for this specific project and at this specific point in time. More cautious now, I was reluctant to become onr of the company's very first clients, but established a good working contact with David Hampton, who purchased a Surphaser for his own Art scanning enterprise and with help of an additional digital photo camera is able to match RGB color textures to the scans he produces. In December 2004, David came to see me and my team in Munich and share experience in the field of sculpture scanning.

4.4.4 Faro Arm and ModelMaker X Sensor

Faro Gold Arm.

After dealing with representatives and engineers in Connecticut, Pennsylvania, London and Moscow, I was happy to find a speaking partner in Germany again. Through my contact with Prof. John Cosmas, co-ordinator of the 3D Murale Project[50] at Brunel University, London, the attention was drawn to the ModelMaker X System, employed by Descam GmbH in Unterhaching near Munich, representing 3D Scanners in Germany.

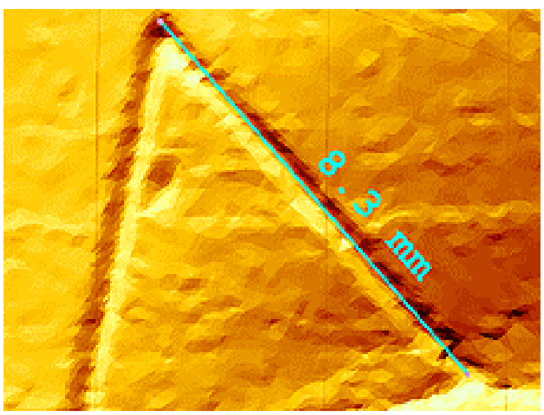
Like the Minolta and 3DD scanners, this system is based on laser triangulation. The scanner head, however, is

50 An international archaelogy project employing 3D measurement and visualisation. Project website: http://www.brunel.ac.uk/project/murale/home.html.

very small and light, and is attached to a 7-axis Faro measurement arm.[51] This miniature scanner head projects a laser beam that captures the object´s surface stripe by stripe while the scanner head is drawn along the object in ca. 8-15 cm distance. The position of the scanner head is determined by precision sensors in the joints of the arm; with KUBE operating software, all movements of the scanner head are accounted for in real-time, so that all measured points are allocated to the same co-ordinate system. There is no need to match single range maps. Due to the high accuracy of the Faro arm, all data fit toghether almost seamlessly.

ModelMaker X.

With the X35 head a stripe of ca. 35 mm wide can be scanned; with a point spacing of 40 points/mm along the projected line (y). Scanning speed is ca. 23,000 points/s; captured points are resampled according to parameters set by control software. With the X140, raw data resolution along the projected line is 10 points/mm, but the stripe is accordingly wider. Maximum stripe width is 140 mm, with a larger working distance from the object (15 cm) and a larger focal depth. The y and z values for the X70 are lying inbetween, with raw data resolution at 20 points/mm along the line. The combination of close-up scanning and high point density allows for scanning finest details, but for judging the over-all accuracy of the sensor + arm combination, the measuring noise of the arm has to be allowed for as



Evaluation of ModelMaker test scan.

51 At that time, the best available arm was the Gold Arm. In July 2003, the Platinum Arm was introduced to the market. As an alternative to Faro, Cimcore arms can be used as well.

well. By scanning expert Dr Duwe, z-noise for the combination of 10-foot Faro Gold arm with X70 scanner head was estimated at ± 20 micrometer.[52]

The main advantages of this system are:

- Varying resolutions can be recorded within a single point cloud file. There is no need to create an over-all model in lower resolution first, then fill this in with smaller, high-resolution patches.
- The recorded model is displayed in real-time, without delay for manual matching. Missing parts can be fitted in immediately.
- Due to the small size of the scanner head and the flexibility of an 7-axis arm, most parts of the sculpture can be reached quite easily.
- Larger sculptures can be scanned from various positions, the files can be matched afterwards, or floor marks are used for shared orientation.

On 5 July 2002, I met with Sigmund Scriba and his staff at Descam's offices. On this Friday afternoon, we made test scans of the well-known little plaster torso with the scratches, among others. In the first round, a small plaster torso was scanned with the X35 sensor completely. Since Descam staff resampled the scan to a simplified grid of 1 mm, the view the scratches was blurred. Subsequently, I had a scan made of a smaller area only, this time without sampling. This point cloud was merged into a mesh file with 0.1 mm grid, clearly showing the scratches.

I also had a scan test with the X70 sensor made, with and without sampling. As could be expected, these scans were slightly less detailed, but still very good. The advantage over the X70 is that the scan stripe is broader and focal depth is larger.
Although I was very impressed by the continuous work-flow and the results, this system seemed to have its limitations as well:

52 Work meeting with Dr Duwe in Lindau on 1 May 2003, see Chapter 4.5.4.

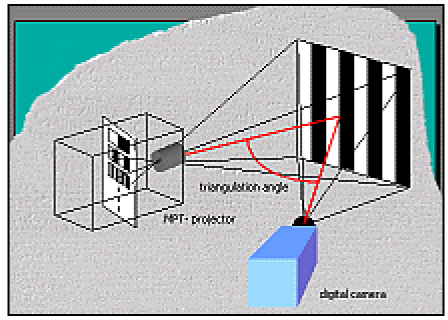
- The system has to be assembled on location; to secure stability of the Faro arm while scanning large sculptures, a heavy-duty tripod has to be used. Our user-colleague David Hampton at Cooper Tyres UK warned us that setting up and calibrating the system could be a cumbersome process.[53]
- Scanning speed is max. 23,000 points per second. With the X70, featuring 70 mm x 20 points/mm = 1,400 points along the line, one can scan 23,000/1,400 = ca. 16 lines/s. When point spacing in scanning direction is set at 8 lines/mm, it takes one second to scan a 7 cm wide stripe of 2 mm length, and one minute to produce a 7 cm wide stripe of 12 cm length. Scanning large sculptures at a high resolution needs patience and strong biceps muscles.
- With a total cost of over 100,000 Euro, I would not be able to invest in this technology on my own. I discussed sharing system use with Brunel University within the framework of the University's multi-media courses, but this scheme proved to be very circumstantial. Descam GmbH offered a scanning service on location, but at that point in time, I was eager to operate the entire survey process autonomously.

Discouraged by David Hampton's critical comments and having no possibility to buy the equipment on my own or rent it without service, I decided to stay in touch with Sigmund Scriba and wait for Brunel University to purchase this system with EU funds first. I maintained my contact with Prof. Cosmas and his colleague Aaron Bergstrom at the North Dakota State University Archaeology Technologies Laboratory, to share our practical findings in the field of 3D scanning.

53 Telephone conversation with David Hampton of 25 July 2002; in practice, no such problems occurred during our museum trips.

4.4.5 Breuckmann OptoTop HE sensors

Looking for still other alternatives, I decide to contact two companies I had not appoached yet: Breuckmann GmbH in Meersburg and GOM GmbH in Braunschweig, both in Germany. According to specifications quoted in an overview supplied by Geomagic Software, both companies would reach a very high resolution and accuracy, using photogrammetric and topometric systems based on the projection of white halogen coded light, instead of laser beams.



Breuckmann fringe projection.

Breuckmann OptoTop HE sensor with small basis.

Whereas the American and Asian markets are dominated by laser systems, this structured light technology was developed especially in Germany in the 1980's and 90's and is extensively used here. Originally applied for deformation and vibration analysis at the M.A.N. Technology Center for Optical Measurement in Munich-Karlsfeld, these methods were taken further by former M.A.N. researchers like Dr. Breuckmann, who founded his own laboratory in 1986; competitor G.O.M. GmbH was founded in 1996. [54]

54 An overview of the development of optical measurement systems in Germany was presented by Dr Hans-Peter Duwe in an unpublished lecture at the PolyWorks 3D user Forum in Lindau, Germany, 3–4 April 2003. See also: Bernd Breuckmann, Bildverarbeitung und optische Messtechnik in der industriellen Praxis - Grundlagen der 3D-Messtechnik, Farbanalyse, Holografie und Interferometrie mit zahlreichen praktischen Applikationen, Franzis-Verlag GmbH, München, 1993, ISBN 3-7723-4861-0.

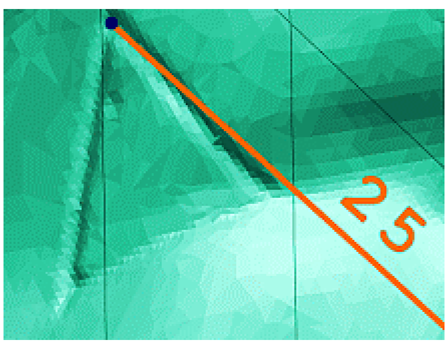
On 2 July 2002, I discussed our project goals with Dr Carsten Reich at GOM GmbH. I purchased a second plaster torso, made fresh scratch patterns and sent it off to Braunschweig. The very same day, I also reached Bernhard Tyborsky at Breuckman GmbH, who invited me to visit the company by the end of July. Breuckmann GmbH was the first company that offered to rent its equipment, so enabling me to apply this high-end technique autonomously. On 29 July 2002, my wife and I met with Dr Bernd Breuckmann and Bernhard Tyborski in Meersburg. Dr Breuckmann showed a genuine interest in the cultural side of my plans and offered to accompany us at a first museum visit free of charge. During the afternoon, the key features of the stripe projection system were demonstrated to us:

- Various stripe patterns are projected on the object, using patented Micro Projection Technique (MPT), during ca. 3 s. A digital camera with a 1280 x 1024 pixel chip[55] records the deformation of the stripe pattern. The software calculates the co-ordinates of 1.3 Million points per scan. Single patches are fitted to the over-all model with OptoCat or PolyWorks software.
- Sensors of different basis lenghts and triangulation angles (20° - 30°) are available, for different Field-Of-Views (up to 180 cm) and resolutions. Using an OptoTop sensor with an image diagonal of 20 cm, corresponding to a resolution of 8 lines/mm, Dr Breuckmann scanned the little torso, matched the patches as they were created and showed us the plaster scratches in high detail, without visible noise and artefacts in the surrounding surfaces. At this x,y resolution of 120 micrometer, z-noise is indicated with ± 10 micrometer and x,y feature accuracy with ± 15 micrometer. An OptoTop HE sensor with a F.O.V. diagonal of 40 cm allows for scanning with a point spacing of 240 micrometer (ca. 4 lines/mm), with z-noise at ± 20 micrometer and x,y feature accuracy at ± 30 micrometer.

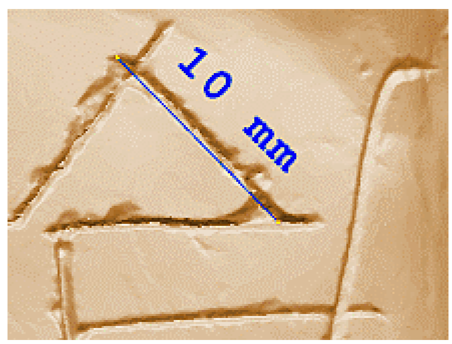
- Using a carbon fibre basis and miniature technique, Breuckmann produces very light, easy to handle sensors (appr. 2 kg each). The complete system can be packed in a flight box and can be transported and assembled easily.

This equipment - being used by major car manufacturers and in the medical field - meets the highest industrial standards of accuracy and reliability.

Although the torso mesh file returned to me by Dr Carsten Reich of GOM was technically flawless as well and the GOM Atos system, featuring two cameras instead of one, is equally accepted throughout the industry, I felt I should accept Breuckmann's friendly offer and do a museum test run with the company´s OptoTop HE sensors. For practical reasons I agreed to select a museum in the geographical neighbourhood of the company's offices.



Evaluation of OptoTop HE 200 (resampled).



Evaluation of GOM Atos[56].

55 Currently, the use of 4 megapixel chips is tested and announced for industrial use both by Breuckmann GmbH and GOM GmbH.

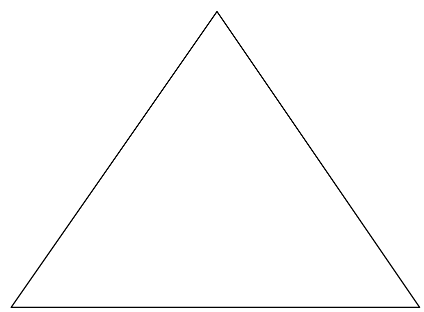
56 Dr Carsten Reich used an extremely high resolution with very small F.O.V.s – a method suitable only for very small objects, like my 13 cm high plaster torso. Additionally, Dr. Reich used paper marks and photogrammetry, to match these small patches – a method that could not be employed by me for fragile plasters in museum situations. For this reason, the results cannot be compared directly.

4.4.6 Technical interim conclusions

After these test scans, I was able to formulate the following interim conclusions regarding 3D data capturing technology for complex objects:

- With modern mobile equipment, it is possible to document the geometric properties of sculptures with an accuracy surpassing that of traditional museum measurement methods - like rules and calipers - by far. Even with high-precision calipers, the spatial qualities or surface structures of sculptures cannot be captured the way modern non-contact measurement methods can.
- When setting up a 3D measurement project, one has to account for the trade-off between:

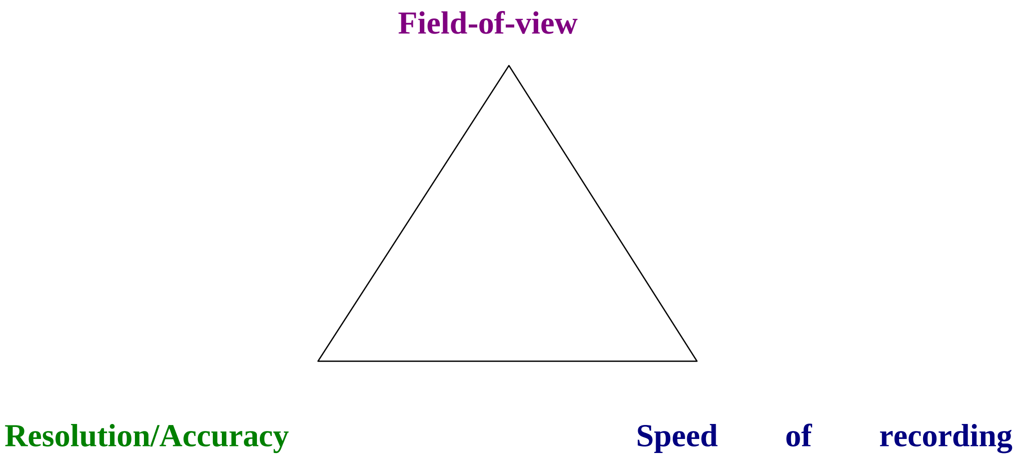
Cost



Resolution/Accuracy **Speed of recording**

Lower-cost equipment, like 3D Digital Corp. and Minolta Vivid 900 (20-40 K Euro) cannot compete with the speed and accuracy of high-end systems like Breuckmann, Faro/ModelMakerX and GOM (>100 K Euro).

- Another trade-off exists between F.O.V., Resolution and Speed:



Obviously, scanning large Fields-Of-View with low resolution – instead of scanning small patches with high resolution - allows for scanning larger areas in less time. The resulting model will be completed earlier, but it will lack detail and accuracy. This is the typical dilemma when working with the Minolta Vivid 900, 3D Digital Corp. Model 300, or a set of Breuckmann OptoTop HE sensors with different F.O.V.s. The Minolta system offers three lenses, Breuckmann offers different sensors[57], the 3D Digital Corp. Model 300 can scan in varying distances from the object with one lens: The principal trade-off remains the same. Especially with larger sculptures, the object has to be captured more than once, using different resolution modes: with low resolution for capturing the over-all geometry, and then with higher resolutions, to fill in details with smaller patches. Creating a large model starting from small patches bears the risk of accumulating matching errors ("banana effect"). Since for scanning in very close distances, covering smaller F.O.V.s, focal depth is smaller as well, much of the information

57 Currently, Breuckmann also offers sensors that can be adapted to different F.O.V.'s on location.

in these smaller patches is masked off when capturing areas with large z-variance.[58]

Although the Surphaser promises to overcome the F.O.V. - resolution dilemma by scanning a large circular area with high resolution, nominal scanning speed of 200,000 points/s is slower than that of stripe projection systems capturing 1,3 million points/s. The Faro arm/ ModelMaker X system has the lowest nominal scanning speed of ca. 23,000 points/s, but other than the four other systems, it allows for generating a complete model without intermediate matching steps and for following the object surface intuitively, so that a single range map represents more than one point of view. Moreover, there is no need to create an over-all model with low resolution first, since the fitting of smaller patches to the over-all shape is guaranteed by the unified co-ordinate system.

For a comparison of technical specifications, I have created an appendix with technical information as supplied by the equipment producers involved. To verify these data by calibration tests in the micrometer or millisecond range was not the goal of my project[59]. The quality of all scanners was judged by making point-to-point measurements within the unmanipulated point cloud to determine effective resolution and the amount of z-noise, documented by screenshots and calculation records. Only in the case of the 3D Digital Corp. Model 300 I was forced to question the specifications given by the company's brochure, since the noise in the measured data was obvious and disqualified this scanner for use in my project.

58 I amply discussed this problem with Stefanie Adolf at Minolta, who was so kind to send me a list indicating the Vivid 900's focal depth for various F.O.V.s. (Letter to the author of 14 March 2003). In London, I had a highly instructive conversation on the trade-offs of 3D scanning with Peter Petrov, Basis Software Inc. and Mike Davies of AG Electro-Optics.

59 For accuracy tests on long-range scanners (Mensi, Cyrax, Riegl etc.), see Böhler, W.;Bordas Vicent, M.;Marbs, A.: Investigating Laser Scanner Accuracy. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIV, Part 5/C15, pp. 696–701, Antalya, 2003 http://www.i3mainz.fh-mainz.de/publicat/cipa2003/laserscanner_accuracy.pdf.

After dealing with various systems and exchanging information with producers and other users for three years now, I must conclude that neither technical specification sheets nor one-day demo meetings nor precision calibration tests in the end can provide that kind of knowledge needed to select the most appropriate equipment for specific projects and locations. Seemingly secondary factors like the weight or the size of a scanner can make it inappropriate for use in an improvised museum environment with fragile items. To estimate the needed scanning time needed for a specific sculpture, hands-on experience is required. One of the most interesting conclusions from working in a dozen different museum situations, scanning both very small (10 cm high) and very large (214 cm high) sculptures presenting different grades of complexity and detail, is that nominal scanning speed alone is not decisive for the efficiency of the total workflow.

After the initial period of getting acquainted with various kinds of equipment, museums visits in Strasbourg and Heilbronn, technically supported by Breuckmann GmbH, provided me with the first bits of practical experience needed to pursue a successful scanning strategy, and confronted me with new problems to be tackled.

4.5 Capturing and evaluating 3D data of Rodin’s monumental ‘Thinker’

4.5.1 First scanning of the Strasbourg ‘Thinker’ plaster

Since I had had already received permission of the Strasbourg Musée d´art moderne et contemporain to survey its monumental ‘Thinker’ plaster, I now planned a trip to this city, together with Breuckmann staff: our first 3D scanning trip to a museum.

Thinker’ plaster in Strasbourg
First photos of Aug. 2002.

The Strasbourg example is an original plaster cast purchased directly from Rodin in June 1907 after an exhibition of French Sculpture. Later, the plaster was stored at the City's University, and used for drawing lessons. In the 1960's, rebellious students smeared the sculpture with paint. Only by the end of the 1990's, the plaster was completely restored.[60]

Workshop at Breuckmann GmbH.

To have a first look, my wife and I visited the Strasbourg Museum on 4 August 2002; back in Munich, we mailed our photos to Breuckmann GmbH. This way, we were able to discuss the situation awaiteing us and plan an appropriate scanning strategy. I suggested to produce scans with a large sensor first, to create an over-all model, then fill in additional details with smaller patches.

Six weeks after the first meeting with Breuckmann GmbH, on 20 Sept. 2002, my wife and I made a trip to Meersburg once more, to get to know the Breuckmann equipment and the software better. During the Friday afternoon, we worked in the

60 Museum documentation, photocopies of Museum catalogue by Rodolphe Rapetti et. al. Editions Scala, supplied by Franck Knoery, Documentalist, by letter to the author of 11 March 2002.

company's survey studio, scanned parts of an airplane model and matched the patches with OptoCat 3D software. On Sunday afternoon, we drove to Strasbourg, where we met again with Dr Breuckmann and his wife, together with sales engineer Bernhard Tyborski.

Scanning in Strasbourg with 3 OptoTop HE sensors.

On Sunday, 22 Sept. 2002, after the museum had closed for the public, our joint team installed topometric and conventional cameras in the large room where Rodin's 'Thinker' is displayed.

After 90 minutes our set-up was complete, so that we could start with the actual survey early Monday morning. For measuring spatial qualities, we used 3 different optoTOP sensors, covering rectangular F.O.V. areas with a diagonal spread of 180, 60 und 20 cm respectively. With the largest sensor, we were able to grasp the total structure of the sculpture within ca. two hours. Another five hours were needed to make additional scans of smaller areas, this time in higher resolutions. Especially the face, the hands and the feet needed extra attention, in order to document the finer details of the modeling.

Range maps are aligned to the over-all model.

Every single scan supplied us with geometrical data of 1.3 Mio points. All range maps were aligned to the total model immediately after scanning, using PolyWorks software on a second PC. Because the sculpture offered enough surface variation, it was not neccessary to use extra measuring marks, that might have sticked to the plaster.

Finally, we used the evening hours to make stereo colour photos from different angles with the Mamiya RZ 67 and a 6 megapixel Jenoptik digital camera. At the end of the day, we had produced over 90 different 3D scans of overlapping segments of the sculpture, resulting in a point cloud of ca. 120 million points, and over 100 large colour slides.

In the following weeks, Breuckmann staff helped us to optimize the fitting of the single range maps and transform the complete point cloud into a .STL model with a point grid of 1 mm. Although the original data contain a still higher resolution, this provisional .STL model seems sufficient to capture the over-all structure of this monumental cast for an understanding of Rodin's modeling performance.

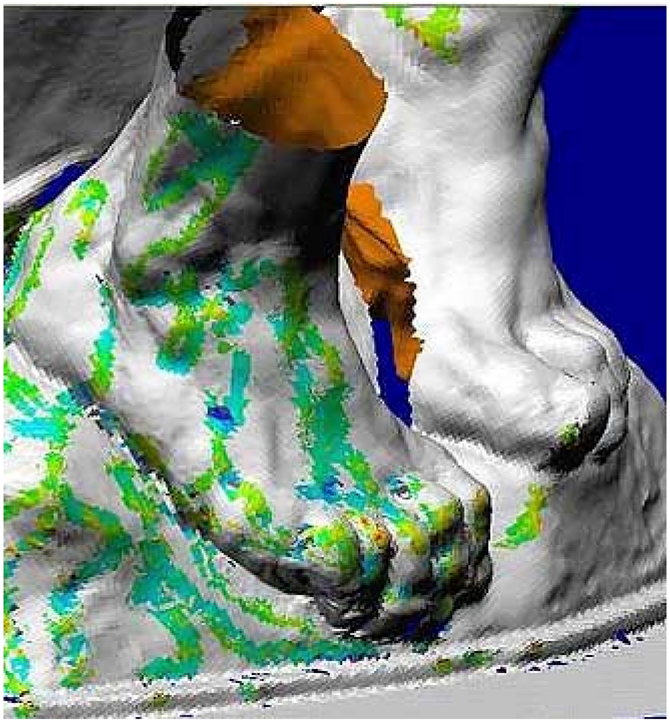
For other sculptures, like Rodin's 'Eve' (71.8 cm high), which I scanned with Breuclmann equipment in Heilbronn in February 2003 with a resolution of up to 8 lines/mm, I created much more detailed models, resulting in a sharp definition of edges and surface structures, like scratches and fissures.

4.5.2 Meeting with Dr Duwe to work with PolyWorks software

After a recommendation by Dr Breuckmann, a co-operation developed with Dr Hans-Peter Duwe in Lindau. Like Dr Breuckmann, Dr Duwe is one of the pioneers of German 3D technology, developed in the 1980's and 90's in the laboratories of M.A.N., Dr Steinbichler, Dr Wolf, Dr Massen and others. Representing the Canadian company InnovMetric since 1999, Dr Duwe introduced me to PolyWorks Software. This is a most powerful 3D software, mostly used for industrial measurement, production and inspection.[61]

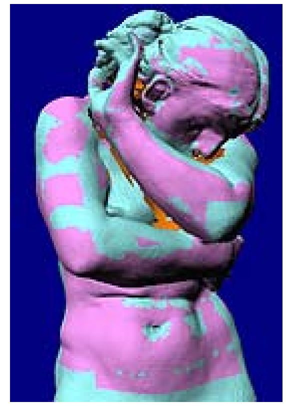
61 For a discussion of the criteria 3D software for cultural heritage recording should meet, see: Böhler, W.;Heinz, G.;Marbs, A.;Siebold, M.: 3D SCANNING SOFTWARE - CIPA, Heritage Documentation. International Workshop on Scanning for Cultural Heritage Recording, Corfu, Greece, 2002.

After Dr Duwe, together with Dr Marc Soucy, the creator of PolyWorks, had visited me in Munich as early as October 2002, I now spent a complete day with Dr Duwe at his offices in Lindau on 28 Febr. 2003. Together, we evaluated the data produced during the museum visits in Strasbourg and Heilbronn and discussed the practical aspects of using PolyWorks for my project:



Controlling the fitting of overlapping range maps.

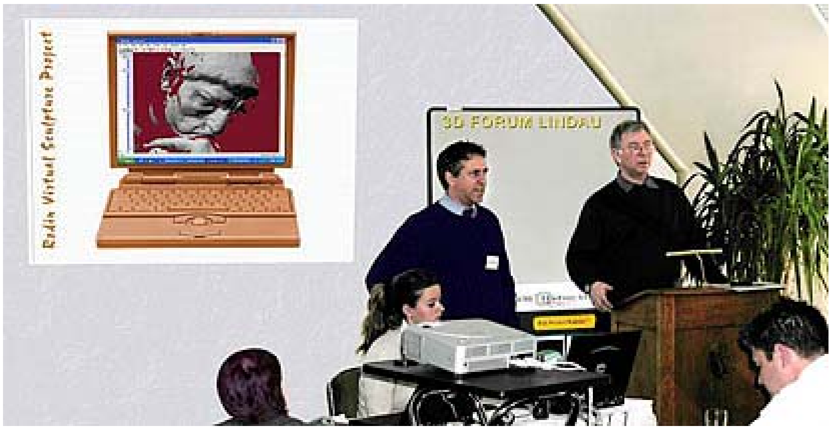
- By n-point alignment and iterating calculations, the **IMAlign** module fits single range maps into the over-all model and improves their orientation, till optimal convergency is reached. Installed on a second computer, this module would allow my team to align captured range maps while simultaneously controlling new data capturing with the first PC, as already practised in Strasbourg, to speed up our workflow. This module can also filter away redundant data in overlapping range maps. The data that were recorded under a better angle or with a higher resolution are selected, while superfluous data


Resolution selected by subgroups in IMAlign.

of inferior quality are removed from the combined point cloud. Through this selection, the virtual model is based on the best data only. The selected patch areas finally have an overlap as small as 4 mm, for example.

- With Polyworks **Inspector**, possible gaps between adjacent range maps can be measured and visualised. These ruptures can be smoothed out later by using IMEdit.
- By using **IMMerge**, the - now cleaned up - point clouds can be transformed into polygon meshes very efficiently, creating a grid of triangles.
- With **IMCompress**, these meshes files can be further reduced, taking the curvature of the surfaces into account. The total amount of data is reduced, but finest details and sharp edges still remain well-defined and crispy.
- With **IMEdit**, the polygon meshes can be edited and retouched. Small holes can be filled automatically or using Beziers surfaces, so that the filling patches are optimally adapted to the surrounding surfaces.

Invited by Dr Duwe, I presented the Rodin Virtual Sculpture Project at the annual 3D Forum taking place in Lindau, Germany, on 3 and 4 April 2003, focussing on the newest developments and applications of optical 3D measurement technique.



Presenting the project at the 3D User Forum in Lindau. Photo: Ms Duwe.

4.5.3 Second Scanning of the Strasbourg 'Thinker' plaster

In September 2002, I had noticed that certain smaller areas of the 'Thinker' plaster could not be reached with the Breuckmann sensors, due to the principle of triangulation. While the projecting unit was able to project stripes on, for example, the inside of the hands, parts of these surfaces remained occluded to the sensor's camera eye, recording the scene from a slightly different point of view. Although quite light and easy to handle, the Breuckmann sensors could not always be optimally positioned to capture the complete space between chest, chin and arms of the large 'Thinker'.

Scanning the feet of the ‚Thinker' with Faro Gold Arm and ModelMaker.

To overcome these problems, I decided to make a museum test run with the miniature ModelMaker X Sensor combined with a 10 foot Faro Gold Arm. On 28 April 2003 I made a second trip to the Musée d'art moderne et contemporain, accompanied by my friends and assistants Alida Kreutzer and Stefanie Prinz, and by Descam GmbH technician Udo Stelzer.

During a 14 hour scanning session, we acquired altogether ca. 900 separate scan stripes with a lateral resolution of 0.2 mm – 10 times higher than with the large 180 cm F.O.V. Breuckmann sensor. This time, the Faro Arm in combination with floor marks supplied us with a unified co-ordinate system from the very beginning, thus eliminating the need to match and align single patches. Even if we count only two minutes for 3-point matching and fine alignment of single range maps and another minute for re-positioning a conventional sensor, for producing 100 rangemaps with a conventional optical system mounted on a tripod 5 hours of working time are spent without capturing new points. Moreover, the direction of the ModelMaker scan head is intuitively adapted to the surface orientation while scanning single stripes, so that every stripe contains the results of several uni-directional range maps as made from fixed sensor positions. Thirdly, range maps can be produced more efficiently, since only little overlap to adjacent patches is needed. Since the scanning operator can see the stripes accrue on the screen in real-time, already fitting to the rest of the model, this method avoids too many redundant data – which slow down data processing. During this and further museum visits, the combination of these three time-saving characteristics of data acquisition proved to be highly efficient for scanning complex sculptures that cannot be captured completely from a few perspectives.[62]

4.5.4 Second meeting with Dr Duwe to work with PolyWorks software

To check if the new ModelMaker SAB2 file format actually could be read by PolyWorks, I visited Dr Duwe in Lindau again on 1 May 2003. We managed to load the ModelMaker files of the Strasbourg 'Thinker', create a new grid for all measured points with a regular 0.4 mm distance between all points, and convert these organized

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62 In 1998, Guido Heinz tested the Faro Arm for purposes of 3D data capturing as 6-axis arm for tactile measurements, without scanner head. Accordingly, this equipment seemed inappropriate for capturing complete sculptures. See: Heinz, G.: Comparison of Different Methods for Sculpture Recording. - ISPRS Commission V, Symposium, Hakodate, Japan, 1998. International Archives of Photogrammetry and Remote Sensing, Vol. XXXII, Part 5, pp. 557–563. Hakodate – 1998. See: http://www.i3mainz.fh-mainz.de/publicat/isprs_heinz98/comprecording.html - LASER%20SCANNING%20SYSTEMS
By now, Faro inc. offers it own brand of scanner heads.

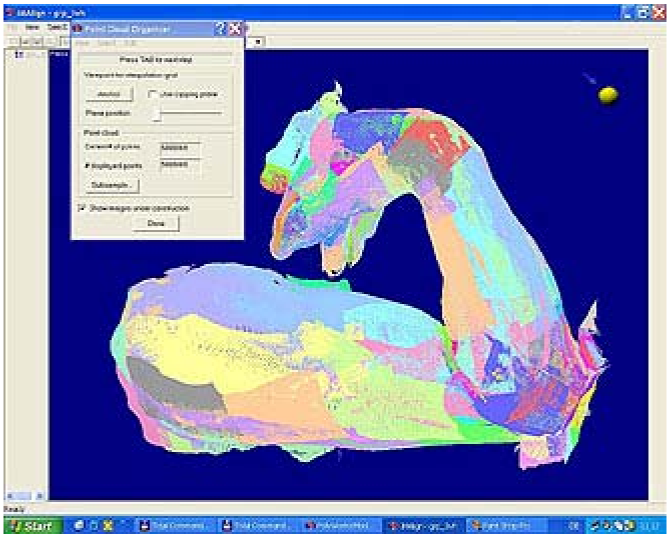

Evaluating Faro/ModelMaker scans.

point clouds into meshes, which were stored as PolyWorks PIF format files (PolyWorks Interchange Format) (Ill.1). After these steps, the mesh files can be processed and edited with other PolyWorks tools. In this format, the ModelMaker data can also be combined with data produced by the Breuckmann sensors, to create a complete, combined model from various data acquisition sources.

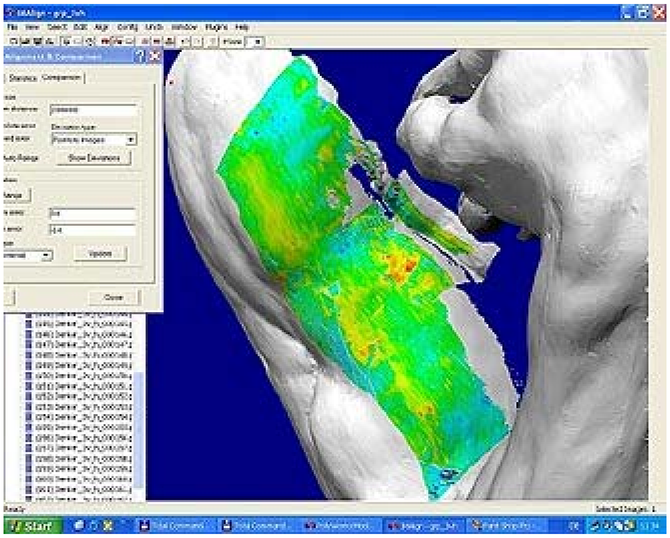
Using IMAlign, the fitting of the scan stripes acquired with the ModelMaker X/Faro Gold Arm equipment data could be noticeable improved. After only two iterations, the scan stripes were intertwined much better (Ill. 2) The improvement could be checked by measuring the fitting quality in PolyWorks Inspector. Green and turquoise areas indicate optimal fitting; only very few cleavages remained (orange and red areas) - with red areas indicating a deviation as small as of 0.4 mm (Ill. 3).

With the Faro/ModelMaker combination, nearly complete scans of the inside of the hands had been made (Ill. 4). We were now able to inspect any remaining small holes, for example between the fingers of the sculpture. During our session, Dr Duwe demonstrated again how such minor deficiencies can be repaired using PolyWorks IMEdit (Ill. 6). Version V.8 even allows for automatic filling of holes by means of curved Beziers surfaces. By masking and isolating single parts of the sculpture, we were able to view and edit single surfaces that normally are occluded by other parts.

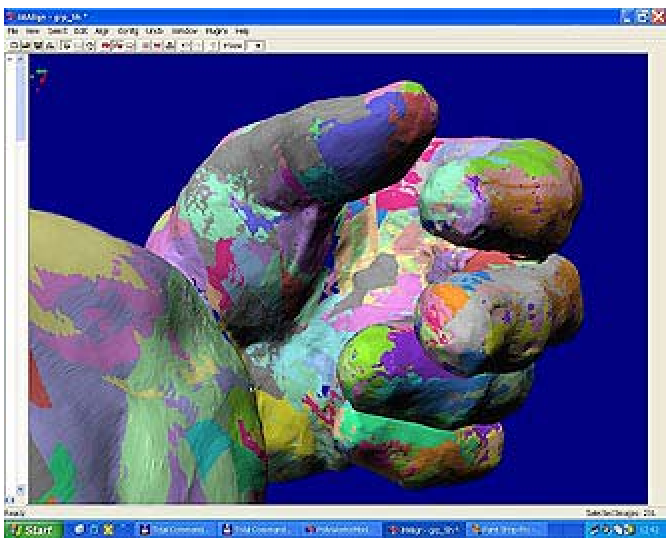
A closer view of our virtual model also revealed some minuscule artefacts, e.g. traces of uneveness in the surface of single scan stripes, mainly caused by an infinitesimal slackness of the Faro Gold Arm during the scan movement. Although such deviations from the ideal plane amounted only to ca. ±20 microns, according to Dr. Duwe, I hoped to reach even better results with the ModelMaker System as soon as the new Faro Platinum Arm would have been released.



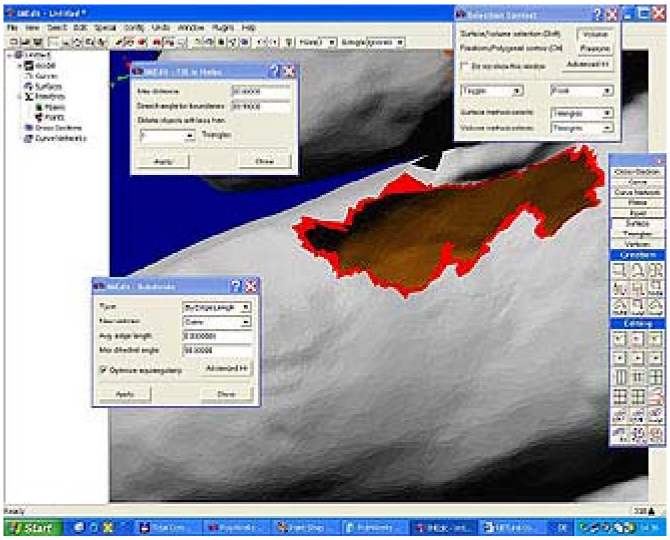
1. Reorganizing the point clouds in PIF format.



2. Controlling the convergence of overlapping scan stripes.



4. Inside view of left hand.



5. Marking the boundary of a hole, to prepare for filling with Beziers surfaces.

4.5.5 Scanning the Poznan 'Thinker' plaster

In the first days of November 2003, after visiting two other museums in France in Switzerland in September and October respectively, my team could at last make its long-planned trip to Poland.

Already in January 2002, I had met with the Curator of the National Museum in Poznan to exchange information on the monumental 'Thinker' plaster donated by P. W. Uhle to the Kaiser-Friedrich-Museum in January 1905 (see Chapter 2.2). In the meantime, I had been able to collect background information on the Uhle family; P.W. Uhle had been a friend of Georg Treu, the Director of the Dresden Royal Sculpture Collection[63].

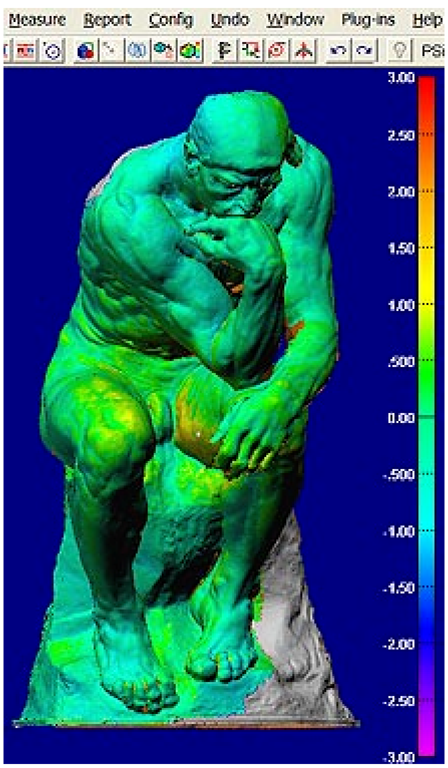
Since January 2002, our visit to Poznan had been postponed several times, since I wanted to be sure that this long and complicated trip across the German-Polish border - at that time quite difficult because of bureaucratic customs regulations - would be effective. Since July 2003, I had been waiting for the new Faro Platinum Arm to become available, which was to deliver even better scans than the Gold Arm.

After finally arriving at the National Museum, we needed ca. 27,5 hours of scanning to capture the complete sculpture, with a lateral resolution of 0.2 mm as well. We also created stereo photos with the Mamiya RZ 67, detail shots with a 6 megapixel Jenoptik digital camera and a video documentation, like in Strasbourg.

63 For evidence of this relationship, see the note by Rodi's secretry Cheruy of 19 Jan. 2003, published by Anna Tahinci, The collectors of Rodin's sculptures in his lifetime, doctoral dissertation, defended at the University of Paris I, Panthéon-Sorbonne in Febr. 2002, p. 1175.

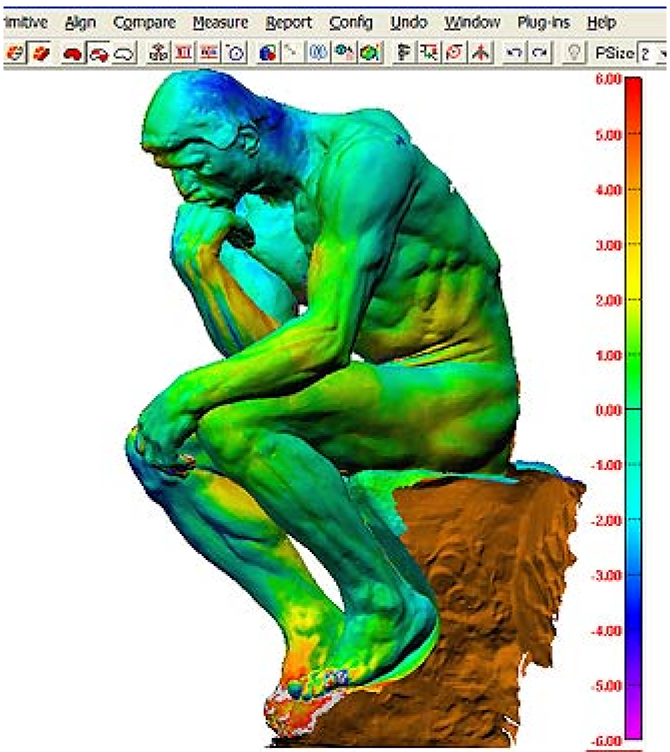
4.5.6 Morphological comparison of the Strasbourg and Poznan 'Thinker'

On 15 Dec. 2003, I met for a third work meeting with Dr Hans-Peter Duwe in Lindau, to produce an exact comparison of the Strasbourg and the Poznan 'Thinker' by means of PolyWorks Inspector Software. With this software, the exact formal differences between two objects can be measured and visualised, by offsetting one mesh file against another dataset acting as a reference. Once the optimal fitting has been determined, the result of subtracting the volumes is presented as a 3D difference model, with a colour scale indicating the amount of deviations for each pair of points.



As a first step, we checked if the scans of the Strasbourg 'Thinker' made with Breuckmann equipment in September 2002 and with the Faro Gold Arm/ModelMaker combination actually were congruent to each other. A 3D difference model based on two .stl files shows the volumes represented by these two data sets are actually as good as identical, with an offset of ca. 0.5 mm in legs, lower belly and left forearm, and max. 1 mm at the inner thighs and dexter side knee. By further balancing the alignment of single range maps within each model and the position of the two models in relation to each other, this result may even be improved, but since for the sake of our comparison, the resolution of both .stl models had been resampled to a 1 mm (Breuckmann) and 2 mm (Faro/Modelmaker) minimum point distance respectively, a fitting better than 0.5 mm cannot be accurately verified by evaluating the resulting difference model anyway.

As a second step, the Strasbourg ‘Thinker’ was compared to the Poznan ‘Thinker’, based on the models created with the Faro Arm/ModelMaker equipment.
A height measurement with the help of a virtual caliper resulted in an height of 182,886 cm for the Poznan ‘Thinker’, whereas the Strasbourg plaster showed a height of 182,481 cm; as a floor reference, a geometric plane was constructed, based on the outline of the wooden board directly underneath the plasters, so that only the plaster sculptures themselves and not their wooden support was considered for height measurement. This difference of 4 mm in relation to an average height of ca. 182,7 cm for both plasters amounts to 0,22% of total height.



3D difference model: Strasbourg off-set against Poznan.

The coloured difference model points out a horizontal offset of up to 4 mm in larger areas as well, demonstrating that the upper body, especially the head of the

Strasbourg ‘Thinker’ - as compared to the Poznan example - is very slightly leaning to its dexter side. Of course, one might as well say instead, the Poznan ‘Thinker’ is leaning over to its sinister side. To determine if one of the plasters is actually "deformed" while the shape of the other is "normal" or "correct", a comparison to still further examples of the large ‘Thinker’ would be needed, or to the original mould. Since both examined plaster casts were purchased from Rodin directly during his lifetime[64], according to the correspondence exchanged with the artist, both plasters have always been accepted as original. It is very well possible, however, that the mould forms did not fit together precisely the same way when the plasters were produced, or that mould forms have been exchanged or repaired during the time between the two casting procedures. In a letter of 30 Jan. 1909, Rodin complained to Raoul Warocqué, who had asked him for a monumental ‘Thinker’ plaster for his Charleroi Museum at an affordable price, that he had to charge at least 3,000 Francs, because his mould had to be repaired: “Ces grosses pièces ont toujours quelque chose.”[65]

Whatever the precise cause for this small deviation may have been, it demonstrates that plaster casting techniques during Rodin’s lifetime allowed for a very small play; without precision 3D measurements, this variance could not have been detected and documented.

More significant, local anomalies could alo be documented, like the false repair of the left foot in Strasbourg and a falsely restaurated left hand of the Poznan ‘Thinker’. In these cases, additional comparisons by means of photos of all known large ‘Thinker’ plasters helped me to discern which form was normal and which not. Additionally, I was able to consult photos taken before and after a restauration of the Poznan ‘Thinker’ in May 2003: Before this action, some fingers of the left hand had

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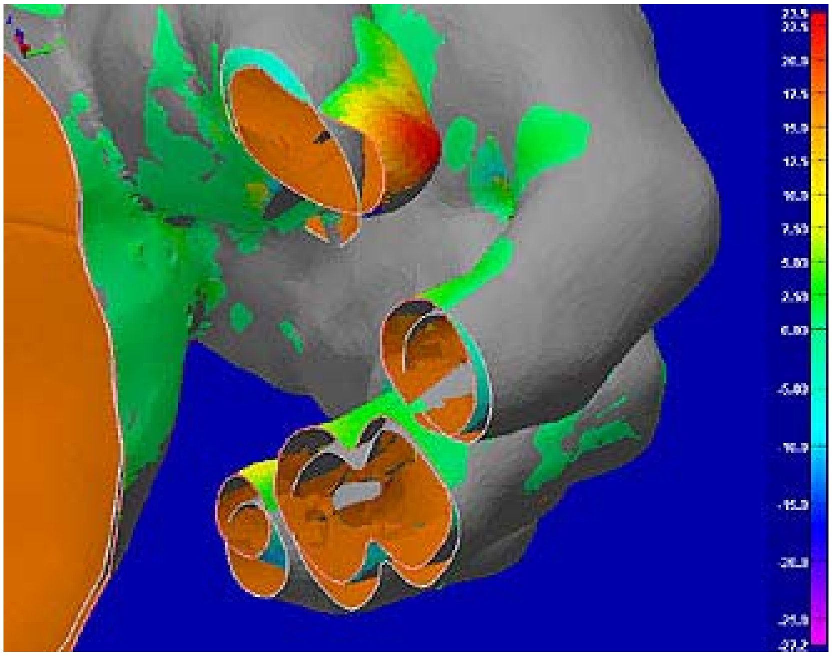
64 For an overview of Rodin scultures publicly exhibited and subsequently sold during his lifetime, see Alain Beausire, Quand Rodin exposait. Publication de la thèse d'Alain Beausire soutenue en 1984 à l'université de Paris-Sorbonne, Musée Rodin, Paris, 1988.

65 Quoted by Anna Tahinci, The collectors of Rodin's sculptures in his lifetime, Doctoral dissertation, defended at the university of Paris I, Panthéon-Sorbonne in February 2002, p. 292–293.

their extreme parts missing, during the restauration especially a far too long piece of thumb had been added.

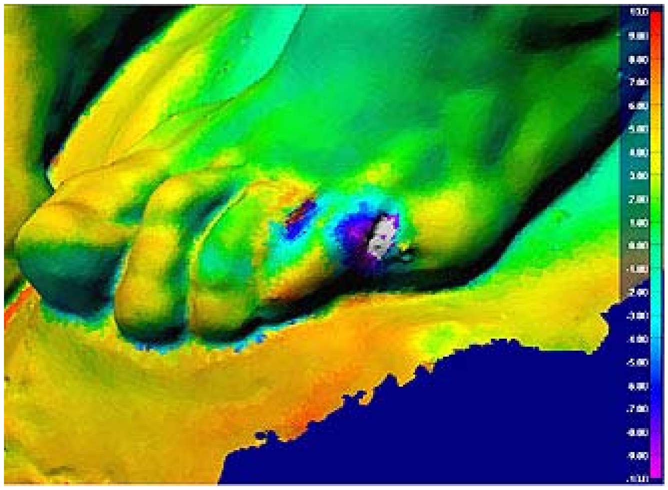


Cross-section inspection of left-hand fingers Strasbourg -Poznan.

Cross-section images generated from the 3D difference model show exactly at which point the shapes of the Strasbourg and Poznan left-hand fingers begin to diverge.

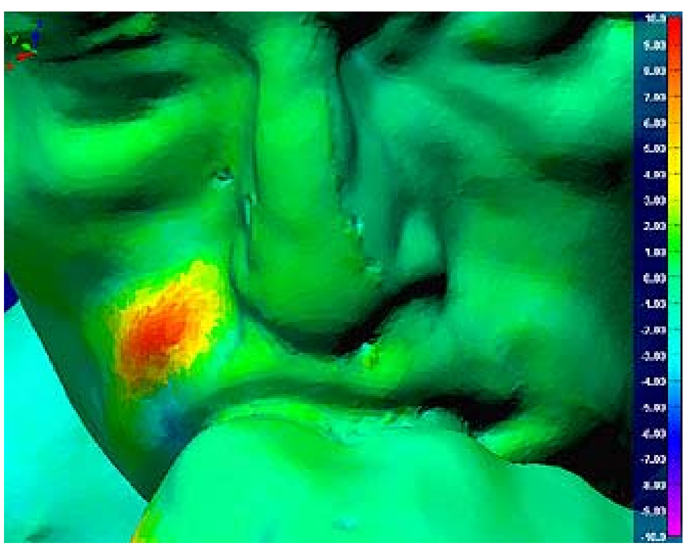
With the help of these data, it would be possible now to correct the false repair of the left-hand fingers in Poznan.

The same would be possible for the two smallest toes of the left foot of the Strasbourg ‘Thinker’, of which only rudimentary residues have survived, so that this foot seems to miss a complete toe. Already during the 3D Forum in Lindau in April 2003, I had been able to indicate this surprising phenomenon by means of a photo comparison. Only the 3D difference model, however, allows for an exact 3D plotting of the missing form.



Damaged left foot, small toes missing in Strasbourg.

Finally, we detected a bump on the dexter cheek/upper lip of the Strasbourg 'Thinker', that only became apparent through our geometric comparison with the Poznan 'Thinker'. At its peak, this elevation amounts to ca. 10 mm. I had no opportunity yet to investigate the cause of this small anomaly.



Strasbourg: Elevation on the upper lip/cheek, dexter sidenge of tasks has notly one report on meang.

After meeting with Dr Duwe, I contacted various sculpture experts, to discuss the function of three small holes found in the chest and under the left armpit of the Poznan ‘Thinker’. The edges show the fine fibre material used to reinforce the plaster - a technique employed for example by Eugène Guioché, one of Rodin's mouleurs, who added straw to produce light, yet stable plaster casts. In his Rodin biography, Grunfeld relates to an account by Jakov Nicoladze, who worked with Rodin in 1909, six years after Lebossé completed the enlargement of the ‘Thinker’:

> “Eugène used green soap as a coating when making the casts, and mixed the pouring plaster with finely chopped straw, which he beat with a brush like a housewife whipping egg whites. 'In this fashion he cast all the separate parts of the figure, and after they were assembled he would reinforce the inside of the cast with tape dipped in the same mixture of straw and plaster'.(...) 'Their[66] work was fantastically light and strong', reports Jakov Nicoladze, the Russian sculptor who worked in the Meudon ateliers for a year and took careful notes on what he learned there. 'They were able to cast enormous sculptures, and their casts were so thin-skinned that, for example, one man alone was able to lift the Penseur.'”[67]

66 Refers to father and son Guioché.

67 Jakov Nicoladze, A Year with Rodin, p. 51, quoted by Grunfeld, Rodin: a Biography, Hutchinson Ltd, London, 1988, p. 557. Other plaster casts are reported to have been reinforced with hemp (e.g. Victor Hugo, Oslo) or horse hair (e.g. ‘Thinker’, 72 cm, Béziers).

5 Epilogue

Combining a thorough analysis of sculptural production techniques and the materials used with morphological 3D comparison could further deepen our understanding of the question, how and when these two ‘Thinker’ plasters - or any other set of sculptures - have been manufactured and how their forms may have been modified over time by accidental damage, false repair, humidity, maybe even by mould-taking - a possibility uttered by Dr Alain Beausire with regard to the Poznan plaster . It may help us to determine, which sculpture is authentic, and which one not. And even if both sculptures have impeccable provenance records - like in the case of the Strasbourg and the Poznan ‘Thinker’ - and in this respect can pass as equal, still the fascinating question remains, which of them is “more equal”, as compared to an original model, that by now may have been destroyed - as is the rule for the clay models Rodin created or the enlargements directly coming from Lebossé’s hand[68] - but maybe could be virtually reconstructed by eliminating contingent qualities and distilling the basic form from an available set of casts.

Within the limited scope of this article it is not possible to present and discuss all background information I gathered on these and other ‘Thinker’ plasters, nor all the chances offered by 3D technology. Not all aspects of the issues touched upon in this text can be elaborated here in detail. Research on the definition and meaning of the original in Rodin’s work, a profound politological analysis of the controversy between the Musée Rodin and the Canadian museums, the role of the Gruppo Mondiale Est and other collectors who have been trading with the ex-Rudier plasters, a report on the other museum trips I made with my team and an evaluation of all data acquired: All this must be presented at another occasion.

68 According to Elsen, Lebossé worked in clay; from the ready enlargements, plaster moulds were taken. See: Albert Elsen, The Thinker and the Dilemmas of Modern Public Sculpture, Yale University Press, 1985, p. 81.

Cross-section of the 3D difference model showing
matching/diverging contours at a pre-defined level.

This paper my have sufficiently demonstrated, however, that conventional methods of measuring sculptures are neither precise nor explicit and unambiguous enough for properly defining the shape of the work and detecting morphological deviations. Especially in the case of a sculptor like Rodin, who bequeathed us many thousands of sculptures and fragments, related to each other by intricate processes of modification, replication, marcottage, assemblage, enlargement and reduction, mobile 3D documentation is a most appropriate and precise, still affordable resource for analysis, comparison, conservation and presentation. The significant and coherent collection of digital sculpture built in the course of my project may function, among others, to advance an intensified scientific interest and aesthetic pleasure in the documented works and promote a more extensive use of high-quality 3D data capturing in the cultural heritage field.

6 Bibliography

6.2 Books On Auguste Rodin

Literature on Rodin is abundant, not to say overwhelming. For the purpose of this presentation, I compiled a small list of books directly referred to in this paper:

Anna Tahinci. *The collectors of Rodin's sculptures in his lifetime*. Doctoral dissertation, defended at the University of Paris I, Panthéon-Sorbonne in Febr. 2002.

Monique Laurent. *Le Penseur*. Published by the Sayegh Gallery, Paris, 1999.

Rodin, *Plasters & Bronzes, Robert Gordon Private Editions,* for Gruppo Mondiale Est, 1999, with text by Dr Schaff and photos by Mario Carrieri.

John Tancock. *The Sculpture of August Rodin - The Collection of the Rodin Museum.* Philadelphia, 1976, 2nd printing Philadelphia Museum of Art, 1989.

Frederic Grunfeld, Rodin: a Biography, Hutchinson Ltd, London, 1988.

Alain Beausire. *Quand Rodin exposait. Publication de la thèse d'Alain Beausire soutenue en 1984 à l'université de Paris-Sorbonne.* Musée Rodin, Paris, 1988, ISBN 2901428231.

Albert Elsen. *The Thinker and the Dilemmas of Modern Public Sculpture.* Yale University Press, 1985.

Albert E. Elsen, Albert Alhadeff. *Rodin Rediscovered.* National Gallery of Art, Washington, 1981.

Jacques de Caso, Patricia B. Sanders. *Rodin's sculpture: a critical study of the Spreckels Collection.* California Palace of the Legion of Honor. 1977, Fine Arts Museums of San Francisco.

Athena Tacha Spear. *Rodin Sculpture in the Cleveland Museum of Art*, 1967, Cleveland Museum of Art, Ohio.

George Grappe. *Auguste Rodin.* Phaidon Editions, Paris/George Allen & Unwin, London, 1939.

Truman Bartlett, “Auguste Rodin, sculptor”, in Albert E. Elsen, *Auguste Rodin: Readings on his Life and Work.* Englewood Cliffs, N.J., 1984, p. 84 (reprinted from the American Architect and Building News, XXV, Nos. 682-703, 19 Jan-15 June 1889.

6.2 3D scanning, especially in the cultural heritage field

Literature on 3D scanning and its various applications in the cultural heritage field has been expanding at rapid rates over the last few years. Many recent projects, lectures, conference proceedings etc. are published over the Internet – a fast medium for a fast-developing field of interest, mirroring the rapid pace of technological development. I selected some publications with direct relevance to the subject of this paper, with an emphasis on Germany and the research done at the specialised i3mainz-Institute of the Fachhohschule Mainz:

6.2.1 Online overviews of methodological articles

Literaturliste codierter Lichtansatz, Phasenshiftverfahren, Bündelausgleichsrechnung, mit Anwendungen, Stand: Avialblae at http://apollo.fh-nuertingen.de/~ag3d/litlist.html (07.05.2004).

Lectures on Photogrammetry, by Dr. C.P. Lo , Department of Geography, University of Georgia, currently availabe at http://www.ggy.uga.edu/courses/geog4430_chpanglo/lecture.html.

Publications of the i3mainz Institute, Mainz, Germany. available at http://www.i3mainz.fh-mainz.de/db/publikationen_zeit?jahr=alle&x=66&y=8.

6.2.2 Small selection of relevant articles, papers and books

2004

Kwan-Yee K. Wong and Roberto Cipolla. *Reconstruction of sculpture from its profiles with unknown camera positions.* Draft version for IEEE TRANSACTIONS ON IMAGE PROCESSING, currently available at: www.cs.hku.hk/~kykwong/publications/kykwong_tip04.pd.f

Böhler, W.;Bordas Vicent, M.;Heinz, G.;Marbs, A.;Müller, H. *High Quality Scanning and Modeling of Monuments and Artifacts*. Proceedings of the FIG Working Week 2004, May 22-27 - Athens, Greece. Published by FIG. – 2004, http://www.i3mainz.fh-mainz.de/publicat/boehler04/WSA2_2_Bohler_et_al.pdf.

Böhler, W.;Marbs, A. *3D Scanning and Photogrammetry for Heritage Recording: A Comparison*. Proceedings of the 12th International Conference on Geoinformatics, June 2004, pp. 291-298 - Gävle, Sweden – 2004, http://www.i3mainz.fh-mainz.de/publicat/boehler04/MarbsBoehler_Gaevle2004.pdf.

Böhler, W. “Dreidimensionale Erfassung von Denkmälern” in: Zipf, A. und Coors, V. (Hrsg), “3D-Geoinformationssysteme. Grundlagen und Anwendungen”. Wichmann Verlag Heidelberg. ISBN 3-87907-411-9 - 2004.

2003

Böhler, W.;Bordas Vicent, M.;Marbs, A. Investigating Laser Scanner Accuracy - The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIV, Part 5/C15, pp. 696-701 - Antalya – 2003, http://www.i3mainz.fh-mainz.de/publicat/cipa2003/laserscanner_accuracy.pdf.

2002
Marbs, A. *EXPERIENCES WITH LASER SCANNING AT i3mainz - CIPA.* Heritage Documentation - International Workshop on Scanning for Cultural Heritage Recording - Corfu, Greece – 2002, http://www.i3mainz.fh-mainz.de/publicat/cipa2003/laserscanner_accuracy.pdf.

2000
Trautner, K. Walcher, M. Krauß, G. Leuchs, B. Bodermann, H. R. Telle. *Interferometrischer 3D-Sensor zur berührungslosen Vermessung technischer Oberflächen*, VDI Berichte Nr. 1572, 2000, available at: www.kerr.physik.uni-erlangen.de/Veroeffentlichungen/InMik/BAMI-vdi-berichte_1572.pdf.

1998
Paul L., Stanke G. *Touchless On-Site 3D Data Acquisition from Freeformed Architectural Details, Statues and other Unique Cultural Specimen for Documentation, Scientific Data Exchange and VR Purposes*. Intern. Workshop: The contribution of Information and Communication Technologies to the Advanced Research of European Religious and Cultural Heritage, Ormylia, Greece, 24. Oct. 1998.

Heinz, G. *Comparison of Different Methods for Sculpture Recording.* ISPRS Commission V, Symposium, Hakodate, Japan, 1998. International Archives of Photogrammetry and Remote Sensing, Vol. XXXII, Part 5, pp. 557-563. - Hakodate – 1998, http://www.i3mainz.fh-mainz.de/publicat/isprs_heinz98/comp-recording.html.

1994

Duwe, H.-P.; Gründer, K.-P.; Wolf, P. M. *Optische 3D-Messungen an Felsbildern und Graffiti*, 4. Internationale Konferenz Zerstörungsfreie Untersuchungen an Kunst- und Kulturgütern, Berlin 3–7 Oktober 1994, DGZfP Berichtsband 45, Teil 1, S. 102-113.

6.2.3 Some recent sculpture scanning projects

- Digital Michelangelo Project, Stanford University, with Cyberware scanner; by now, the project website also refers to scanning with Faro Arm/ModelMaker equipment

- Digital Minerva Project, Archaeological Museum, Florence, Italy, by Visual Computing Lab, with low-cost structured light scanner

- Digitizing of the ancient bronze sculpture of Apoxyomenos with GOM equipment

- Mariensäule Salzburg, scanned with Breuckmann equipment

- Statues on Karlsbrücke Prague, scanned with GOM equipment

- Marburger Dom, ten outdoor saint figures, scanned with Minolta

- 3D recording and visualization of the Cenotaph of Maximilian I. in the Innsbruck Hofkirche, using GOM and Mensi scanners, by i3mainz Institute

- Plaster sculptures made by Paul Klee analysed by Prof. Friedrich Klein and Institut für Angewandte Forschung in Aalen, using a 3D CT Scanner

- Celtic wooden sculptures of Fellbach-Schmiden, counting the number of year rings by means of CT scanning, by Prof. Friedrich Klein, Aalen as well

- Angie Geary, PhD 2001, Royal College of Art, London:'Computer Related Imaging in Conservation: The Visualisation in Three Dimensions of the Original and Present Appearances of European Polychrome Sculpture Using Laser Scan Data, Presented in Virtual and Enhanced Reality Environments'. Scanning with 3D Digital Corp. Model 300 plus colour texture capturing

7 Appendix: Technical specifications of tested scanners

7.1 Konica-Minolta VIVID-900

Type	**Laser light-stripe triangulation rangefinder**
Lens	3 interchangeable lenses Tel f = 25.5mm Middle f = 14.5mm Wide f = 8.0mm
Focus	Auto focus
Distance to object	0.6m - 1.2m
Scan area (x,y)	111mm x 84mm to 710mm x 533mm to max.1300mm x 1100mm
CCD Resolution	640 x 480 points 640 x 480 pixel per colour
Geometrical resolution	x = 0.17mm, y = 0.17mm, z = 0.047mm
Scan time	0.3 - 2.5 seconds
Data file size	1.6MB - 2.4MB
Colour LCD	5.7 inch colour TFT LCD
Memory Card	128MB Compact Flash Memory Card + Adapter
Interface	Fast SCSI
Laser power	690nm, IEC825, CLASS-2
Laser scanning method	High performance galvanometer-mirror
Ambient light condition	< 500lux
Power	AC 100-240 V
Weight	11kg
Dimensions	210mm x 420mm x 326mm
Operating temp.	10 - 35 °C, <65%RH/no condensation

Source: www.minolta-3d.com/products/eng/vi900-tech-en.html.

KONICA MINOLTA PHOTO IMAGING EUROPE GMBH, Instrument Systems Division, Europaallee 11, D-30855 Langenhagen, www.minolta-3d.com

7.2 3D Digital Corp. Model 300

Distance to scanned object	Company specification for z-accuracy in micrometer
25 cm	± 70
45 cm	± 125
50 cm	± 140
60 cm	± 165
90 cm	± 250

Source: Sales brochure supplied by 3D Digital Corporation, March 2002.

The test files for testing Unit Serial Number 3141, 5 June 2002, created by 3D Digital Corp. Technician Yiaobin Song, even show better accuracy for average values, representing complete point clouds measuring the distance difference between two parallel surfaces, for example ± 50 micrometer when measuring in 50 cm scan distance. The problem I was confronted with refers to the measurement noise represented by single bumps or "orange skin" patterns in significant parts of the scanned plane.

3D Digital Corporation, 238 White Street, Danbury, CT 06810, USA www.3ddigitalcorp.com

By now (Dec. 2004), 3D Digital Corp. is offering a new line of models, Optix scanners, that according to Company specifications should provide a 4 times higher resolution and greatly improved accuracy versus scanners of the preceding generation.

7.3 Surphaser Inc. /Basis Software Inc. Surphaser Model 25

Max. Range	1.3 - 16 ft (0.4m - 5m) (Factory Preset)
Field0of-View	0.5 - 10 ft (.15-3m)(Factory Preset)
Viewing angle	22° , 30° , 40° (Factory Configured)
Range accuracy	0.0006" (25 micron)
Angular resolution	0.010°
Angular accuracy	0.003°
Scan rate	200,000 points/sec (software controlled)
Computer Interface	IEEE1394 100/200 MBPS
Dimensions	4.5" x 6.5" x 21" (.12X.15X.5 m)
Weight	11 lb(5 Kg)
Power	50 Watt (110/220 VAC)
Environment	50°F - 100°F (10°C - 40°C)
Laser	Laser diode, 0.68 micron, 4.7mW, Class IIIa

Source: www.surphaser.com/products.htm.

For Focal Range=100 cm, Angular resolution = 0,0182, F.O.V.=40 cm:

(Results from a MS EXCEL spreadsheet kindly supplied by Mike Davies, AG EO)

Angle from Middle	**Distance Between 2 consecutive samples**	**d1**	**d2**	**% increase**	**Lines/mm**
degrees	micron				
0	317,3	0	0,000317332	0	3,15
5	319,8	0,087489	0,087808359	1	3,13
10	327,2	0,176327	0,176654046	3	3,06
15	340,1	0,267949	0,2682891	7	2,94
20	359,4	0,36397	0,364329313	13	2,78

Surphaser Inc. is a wholly owned subsidiary of Basis Software Inc.

Postal address:1550 McDaniel Drive, West Chester, PA 19380, USA,

www.surphaser.com.

European representative: AG Electro-Optics, UK, www.ageo.co.uk

7.4.1 3D Scanners: Modelmaker X Sensor Series

Sensor Specifications of X-series	**X35**	**X70**	**X140**
SENSOR WEIGHT (g)	295	295	295
RANGE (Z) (mm)	50	100	150
MAX STRIPE LENGTH (Y) (mm)	35	70	140
MIN POINT SPACING (Y) (mm)	0.025	0.05	0.1
SPEED (stripes/second)	30	30	30
LASER POWER	Up to 5mW (class IIIa) / Up to 2mW (class II)		

Source: www.3dscanners.se/Resources/MMXBRO~1.pdf
3D Scanners (UK) Ltd., The Technocentre, Coventry University Technology Park
Puma Way, Coventry, CV1 2TT, United Kingdom, www.3dscanners.com
By now (Dec. 2004), 3D scanners is offering an advanced Z-series

7.4.2 7-Axis FARO ARM

ARM LENGTH	**PLATINUM**	**GOLD**
1.2 m (4 ft.)	±.018 mm (±.0007 in.)	±.0010 in.
1.8 m (6 ft.)	±.026 mm (±.0010 in)	±.0016 in.
2.4 m (8 ft.)	±.030 mm (±.0012 in.)	±.0020 in.
3.0 m (10 ft.)	±.052 mm (±.0020 in.)	±.0033 in.
3.7 m (12 ft.)	±.073 mm (±.0029 in.)	±.0047 in.

Single Point Accuracy, Cone Test.
Source: Technical specification sheets supplied by FARO Inc., 125 Technology Park
Lake Mary, FL 32746, USA , www.faro.com.

7.5 Breuckmann GmbH: OptoTop HE Sensors

Light source: 100 W halogen lamp
Number of projected fringes: 128
Min. measuring time: 980 ms
Sensor weight: 2 - 3 kg
Digitisation (x,y): 1380 x 1040 pixel
Size of measuring range: about 0.8 x 0.6 of image diagonal
Depth of measuring volume: typically 1 / 2 of image diagonal
X,Y resolution: typically 1 / 1.500 of image diagonal
Feature accuracy: typically 1 / 15.000 of image diagonal
Noise (Z): typically 1 / 20.000 of image diagonal

Specifications of typical fields of view

image diagonal [mm] *	50	100	200	400	800
X,Y resolution*[µm]	30	60	120	240	480
resolution limit (Z)* [µm]	1	2	4	8	16
noise (Z)* [µm]	± 5	± 7	± 10	± 20	± 40
feature accuracy* [µm]	± 7	± 10	± 15	± 30	± 60

Source: www.breuckmann.com

Breuckmann GmbH
Industrial 3D Image Processing and Automation
Torenstr. 14, D-88709 Meersburg, Germany