FACES: 3D FAcial reConstruction from anciEnt Skulls using content based image retrieval

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Received 19 September 2003; received in revised form 20 October 2003; accepted 10 November 2003

Abstract

Powerful techniques for modelling and rendering tridimensional organic shapes, like human body, are today available for applications in many fields such as special effects, ergonomic simulation or medical visualization, just to name a few. These techniques, combined with Content Based Image Retrieval (CBIR), are proving to be very useful also to archaeologists and anthropologists committed to reconstruct the aspect of the inhabitants of historically relevant sites like Pompei. This paper presents an integrated system to provide 3D FAcial reConstruction from anciEnt Skulls (FACES). FACES, starting from radiological analysis of an ancient skull and a database of modern individuals of the same area/gender/age, produces a tridimensional facial model compatible to the anthropological and craniometrical features of the original skull. Finally, we compare FACES peculiarities to the most used facial reconstruction methodologies available today.

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1. Introduction

In the last years computer generated imaging (CGI) has been often used for forensic reconstruction [1], as an aid for the identification of cadavers, as well as for medical visualization [2,3], for example in maxillo-facial surgery planning [4]. In fact, 3D modelling, rendering and animation environments today available have greatly increased their power to quickly and effectively produce realistic images of
humans [5]. Nevertheless the typical approach usually adopted for modelling a face is often still too much artistic and it mainly relies on the anatomic and physiognomic knowledge of the modeller. In other terms computer technology is simply replacing the old process of creating an identikit by hand drawn sketches or by sculpting clay, adding superior editing and simulative capabilities, but often with the same limits in term of reliability of the results.

The recent findings of five skulls (see Fig. 1) and several bones from a group of 16 individuals in Murecine (near Pompei), offers the opportunity to combine CGI, craniographic methods [6], and Content Based Image Retrieval (CBIR) technology, to reconstruct the aspect of the victims of this tremendous event.

We start assuming that, unfortunately, what is lost in the findings of ancient human remains, is lost forever. This means that by no way is possible to exactly reproduce a face simply from its skull, because there are many ways in which soft tissues may cover the same skull leading to different final aspects. The problem is even more complicated in the (frequent) case of partial findings, because the missing elements (mandible or teeth for example) could not be derived from the remaining bones [7].

Nevertheless is true that the underlying skeleton affects directly the overall aspect of an individual, and many fundamental physiognomic characteristics are strongly affected by the skull. One of the main purposes of this study, is therefore to correlate ancient skulls to skulls of living individuals, trying, in this way, to replace lost information (for example missing bones and soft tissues) with new compatible data. Additionally, the physiognomic relevant elements that are too much aleatory to be derived from a single compatible living individual, are selected through a search in a facial database (built from classical art reproductions of typical Pompeians) and then integrated in the previous reconstruction. To this aim, in this paper we propose an

Fig. 1. One of the skulls found in the archaeological site of Murecine, near Pompei.
integrated system to provide 3D FAcial reConstruction from anciEnt Skulls (FACES). FACES supports management techniques to access and retrieve images from database uniformly and consistently, according to content based access strategy.

This paper is organized as follows. In Section 2 related works are presented. In Section 3 the proposed reconstruction approach is presented in detail. In Section 4 the results of FACES are presented and discussed. The paper concludes showing directions for future research in Section 5.

2. Related works

Facial reconstruction from skull begins around the end of 19th century, thanks to the work of the German anatomists His and Welker.

The reconstructive methodologies developed over more of a century [8] basically come from two main approaches:

1. the study of human facial anatomy and relationships between soft tissues (skin, fat, muscles) and hard tissues (cranial bones),
2. the collection of statistical facial data about individuals belonging to different races, sex and ages,

and they can be summarized as follow:

- 2D artistic drawing (1),
- photo or video overlay of facial images on a skull image (1),
- 3D reconstruction both with manual clay sculpting or digital modelling (1),
- warping of 3D digital facial model (2).

Some of the methods detailed below rely on a large survey on facial soft tissue depth, measured in a set of anatomically relevant points. Firstly developed on cadavers, this measurement protocol has been improved [9] with data from other races, various body build, and even from living individuals by radiological and ultrasound diagnostic techniques.

2.1. 2D artistic drawing

This is the simplest reconstructive technique, based on the positioning of markers showing soft tissues depths on the frontal and side images of a given skull. Then a contour fitting the markers and the skull itself is traced on a partially transparent sheet. This curve act as a reference for the following drawing phase which involves the anatomic and anthropological knowledge of the identikit artist [10], and lead to a graphic reconstruction of a compatible face (see Fig. 2). This technique is simple and fast and is suitable to give a rough identikit from cadaver remains for forensic purposes.
2.2. Photo/video overlay

The main purpose of this methodology is to compare a face to a skull to highlight matching features [11]. This is achieved via image or video compositing of images (or video frames) of the face and the skull (see Fig. 3), after a scaling normalization.
has been operated. The craniometrical and facial features are defined as measures between anatomically relevant points, and comparing features on the skull image to features on the candidate face image, it is possible to find matches or differences in a set of fundamental physiognomic parameters. Many different versions of this basic technique are possible. The main application is in forensic reconstruction.

2.3. 3D reconstruction

Under this category two kinds of methodologies can be included:

- clay sculpting of the face, which is based on traditional clay modelling;
- digital modelling of a tridimensional face, which make use of software sculpting tools to create and deform surfaces.

In the traditional manual approach the artist starts from a clay copy of a skull, applies the usual depth markers (typically referred as landmarks) and then begins to model a face fitting the landmarks with a process that is the extension in the third dimension of what is showed in Section 2.1. The result is a clay sculpture of a face with optional details as hairs and eyes, for example. An important variation of this technique, is based on covering the clay copy of dry skull with appropriate muscles (see Fig. 4) instead of simply filling the soft tissues depths. In both cases the artist impression is the key to the final result.

In digital modelling the first step is to produce a 3D reconstruction of the skull [12], typically starting from CT data [13], then a facial surface model is created from primitives like B-patches, Nurbs surfaces, Subdivision surfaces, etc. using the landmarks as a reference for the contouring curves. After the 3D mesh is generated, material shaders and textures are applied to enhance the look of the model. The latest modelling tools make even hair modelling possible. Thanks to the powerful lighting and rendering algorithm today available an high level of realism is achievable and the final result is an high-resolution image (or animation) of the reconstructed head, viewed from the desired angle. It is also possible to

Fig. 4. Example of face reconstruction by facial muscles reproduction.
generate a solid reconstruction of the modelled face by stereolithography techniques [14,15].

Both the sculpting and the digital modelling techniques produce a tridimensional output allowing a better understanding of the physiognomy of the reconstructed face, but they share the same subjective approach.

2.4. Warping of 3D digital facial model

The reconstructive methods which belong to this category try to deform (warp) a standard “reference” facial model, selected from a set of models of different sex and race, to fit the landmarks previously assigned on the digital model of the skull. Different warping algorithm have been developed [16,17] to accomplish this task, and in some cases an extension of the classical landmarks set is proposed either introducing new points for soft tissue depth measurement, or obtaining much more detailed depth information via volumetric CT or MR data of the head of living individuals. The warp based methods produce statistically valid face model if the skull belong to one of the races included in the soft tissues database.

Warping based techniques are currently used for forensic, archaeological and surgical reconstructions.

3. Faces

The whole reconstructive process is detailed below in Sections 3.1–3.11. Two reference databases are used: the Craniometrical Database (CD) and the Pictorial Physiognomic Database (PPD). In Sections 3.5 and 3.10 these databases are discussed in detail.

A summary of the described method is showed in Fig. 5.

3.1. The skull

We start selecting one dry skull among the five ones found in Murecine. This skull belonged to a young male, and its overall state of conservation is fine. Fortunately the presence of the mandible make the reconstruction of the lower portion of the face more reliable, because in this case there is original bone tissue to guide the process.

The skull is photographed and then scanned by CT on the axial plane with a step of 1 mm and a slice thickness of 2 mm, so every slice overlaps by 1 mm with the following one. The hires scanning produce a set of images (about 250), as well as a 3D reconstruction of the skull. Additionally, three radiological images of the skull from three orthogonal planes are taken, corresponding to front, side and bottom views. The 3D mesh outputted by CT will be used as a reference to visually verify the compatibility of the reconstructed soft tissues to the dry skull.
3.2. The set of landmarks

The next step is to define on each radiological image a corresponding set of anatomic and physiognomic relevant points, called landmarks, each one with a unique name and number (see Fig. 6).
Because the landmarks are chosen according to their craniometrical relevance, they possibly could not correspond to the points for soft tissue thickness measurement indicated by Moore [9]. In this study we use a set of 19 landmarks, but this number could be extended if necessary. Alternatively it is possible to assign the landmarks directly on the 3D skull mesh generated by CT, in this case the following step (3.3) is not necessary because the landmarks already have tridimensional coordinates. A complete list of the landmarks used is showed in Table 1.

3.3. Adding a third dimension to the set of landmarks

Now we have the same set of points assigned to each of three views corresponding with plane $XY$, $XZ$ and $YZ$. So it is easy to assign to each landmark $L_i$ its

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Table 1
List of landmarks referenced in Fig. 4

<table>
<thead>
<tr>
<th>Landmark #</th>
<th>Location (front view)</th>
<th>Landmark #</th>
<th>Location (side view)</th>
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<tr>
<td>1</td>
<td>Glabellas</td>
<td>11</td>
<td>Onion</td>
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<td>2</td>
<td>Nation</td>
<td>12</td>
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<tr>
<td>3</td>
<td>End of nasals</td>
<td>13</td>
<td>Inner orbital (left, right)</td>
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<td>4</td>
<td>Mid-philtrum</td>
<td>14</td>
<td>Outer orbital (left, right)</td>
</tr>
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<td>5</td>
<td>Upper lip margin</td>
<td>15</td>
<td>Suborbital (left, right)</td>
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<td>6</td>
<td>Lower lip margin</td>
<td>16</td>
<td>Outer nasals (left, right)</td>
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<td>7</td>
<td>Chin-lip fold</td>
<td>17</td>
<td>Beneath nasals (left, right)</td>
</tr>
<tr>
<td>8</td>
<td>Mental eminence</td>
<td>18</td>
<td>Occlusal line (left, right)</td>
</tr>
<tr>
<td>9</td>
<td>Beneath chin</td>
<td>19</td>
<td>Supraglenoid (left, right)</td>
</tr>
<tr>
<td>10</td>
<td>Acoustic meatus</td>
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</table>
tridimensional coordinates \((L_{xi}, L_{yi}, L_{zi})\) simply measuring them on the appropriate plane with respect to a common axis origin. We can easily visualize the landmark set in the tridimensional space of our modelling environment and make any kind of linear or angular measurements between two or more landmarks.

### 3.4. Extraction of craniometrical features

Starting from the landmarks previously assigned we define the \(n\)-tuple of features \((F_1^*, F_2^*, \ldots, F_n^*)\) which are peculiar to this skull and results from the craniometrical tracing of the skull (see Fig. 6). These features are consistent to the features present in CD, they include angles and distances between landmarks, measured on front or side view. A complete list of features is showed in Table 2, where the suffix sx or dx after a numbered landmark means left or right for symmetrical points.

Because each feature has a different relevance from a physiognomic and craniometrical point of view, a different weight is assigned to each of them. The resulting \(n\)-tuple \((W_1, W_2, \ldots, W_n)\), with \(0 \leq W_j \leq 1\) and \(1 \leq j \leq n\), contains the weights relative to \((F_1^*, F_2^*, \ldots, F_n^*)\). These weights are not meant to be dependent from a particular set of features, and if \(F_j = 0\) then \(W_j = 0\).

### 3.5. Searching for similarities in CD

The CD is built on data collected from a radiological survey (see Fig. 7) conducted on thousands of subjects of different ages and sex but all coming from the same geographical area in which the remains were found: Pompei and its surroundings.

Each individual represent a record in the database, and each craniometrical feature, extracted with the same procedure showed before, is stored in a numeric

<table>
<thead>
<tr>
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<th>Angles</th>
<th>Distance</th>
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<td>b+c</td>
<td>20</td>
<td>20</td>
<td>i</td>
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<td>22</td>
<td>22</td>
<td>j</td>
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<td>23</td>
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<td>10–1</td>
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<td>24</td>
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<td>9</td>
<td>11dx–9</td>
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field, as well as the 3D coordinates. Additionally we stored three photographic facial images of each subject, shoot from the same position and during the same session of radiological images. The precise alignment of photo camera and radio-diagnostic device is necessary to allow a spatial correlation between the two different kind of images.

If a digital CT equipment or even a 3D scanner/digitizer were available, an optional field could point to a facial 3D model of each subject, thus avoiding the need for steps 3.6 and 3.7.

Once the database is built, it is possible to search through it to find the record (the modern Pompeian individual) whose craniometrical features are closer to the unknown subject given in input. This task is accomplished by evaluating for each record \( i \) the Craniometrical Similarity Score (CSS) that is calculated as

\[
CSS = \frac{w_1 \left( 1 - \frac{|(F_{ij} - F^*_j)|}{D_1} \right) + w_2 \left( 1 - \frac{|(F_{ij} - F^*_j)|}{D_2} \right) + \cdots + w_n \left( 1 - \frac{|(F_{ij} - F^*_j)|}{D_n} \right)}{\sum_1^n w_j},
\]

in which \( F_{ij} \) is the \( j \) component of the \( n \)-tuple of features \((F_{i1}, F_{i2}, \ldots, F_{in})\), relative to record \( i \), \( w_j \) represent its weight and \( D_j \) is the \( j \) component of an array \((D_1, D_2, \ldots, D_n)\) containing the maximum allowed difference between \( F_{ij} \) and \( F^*_j \) for each \( j \). If any feature is not present in the input skull, due to missing elements for example, then the corresponding term in the CSS formula becomes zero. By Eq. (1), CSS is a value in the range \([0,1]\), where 1 means a perfect match. Ideally CSS should be not less than 80% to use the face as a valid reference for the reconstruction.

3.6. Augmenting the set of landmarks

The aim in CD search is to augment the set of landmarks with new landmarks relative to soft tissues coming from the individual with the highest CSS. In fact, radiological and photographic images of a living individual contain useful information about local thickness and shape of soft tissues, which can replace data missing in the dry skull. To retrieve this data we first normalize photographic images to match the radiological images, and then we blend each pair of images to highlight the facial contours on the underlying skull, thus revealing the soft tissue thickness in many relevant point of the head for each plane.
3.7. Modelling the facial surface

The augmented set of landmarks and the set of photographic images can be used to guide the 3D modelling of the “best match” face. The simplest modelling technique is to visualize the landmarks as 3D points inside the modelling environment, mapping the three photo-images on three orthogonal plane so that for each view all the landmarks are properly positioned. Using these visual references we can draw a sequence of cross-sections whose interpolation result in a surface model of the head. B-patches as well as Nurbs can be used for this purpose. An interesting alternative to manual modelling is to generate the model from a set of stereoscopic images of the head as in [18]. In this case for each record the CD should also contain three pairs of images acquired from a slightly different angles. Whatever the technique adopted, the final result is the 3D model (see Fig. 8) of the head with the maximum CSS.

3.8. Warping the rough face model to fit the original set of landmarks

If the CSS of the reconstructed head is not equal to 1 (and this will probably always be true) then we would like to modify the shape of this model to better fit the craniometrical features of the found skull.

This kind of tridimensional deformation of a mesh, based on vertex relocation by a specific transformation of coordinates, is usually referred as a “warping”.

More precisely, we want to move every bone landmark $L_i$ of the “best match” case for which result $|L_i - L^*_i|\neq 0$ (where $L^*_i$ is the corresponding landmark on the dry skull) to a new position that correspond to the coordinates of $L^*_i$. The purpose is to affect the polygonal surface local to $L_i$ using the landmark as an handle to guide the transformation. Many different algorithms are available to accomplish this task, but we chosen a free form deformation which simply works assigning to the input mesh a

Fig. 8. Rough face model.
lattice with \( n \) control vertex (our landmarks \( L_i \)) and by moving them (to \( L^*_i \)) it deforms smoothly the surrounding surface.

After warping is applied, the face model fit better the dry skull, and this match can be easily verified visualizing at the same time the skull mesh (from CT 3D reconstruction) and the face model with partial transparency.

3.9. Texturing and shading

At this point we can apply material shaders to the head model, to enhance the realism of the reconstruction. We define a material for skin, with a texture assigned for the diffuse channel and a shininess map to simulate the different reflectivity levels present on actual face skin. Both the textures are mapped cylindrically on the mesh. For the diffuse texture we could well use the photographic images relative to the best match case present in \( CD \), simply editing them with a photo-retouching software. To fine tune the assignment of mapping coordinates to mesh vertices we found very useful to make an unwrap of the mesh, in this way has been possible to interactively edit a planar version of the facial mesh thus simplifying this task.

3.10. Searching for missing elements in the physiognomic database

The result of the previous nine steps is the creation of a 3D model of a bald head whose craniometrical features are compatible to the ones belonging to the found skull, and whose soft tissue thickness come from a living individual probably with similar anthropological features.

We want now integrate this tridimensional identikit of an unknown Pompeian with physiognomic element such as eyes, lips, nose and hairs coming from the only reliable source we have, the paintings and sculptures made from artists contemporary to Vesuvio eruption, who are supposed to be inspired, in their works, from typical local subjects.

The technology we used to access and retrieve visual information from the previously mentioned sources is known as CBIR [19].

So we introduce the PPD, built as a collection of images reproducing Pompeian classical arts. This database is based on the work by Abate et al. [20] and it allows, via a query by pictorial example, to retrieve images (see Fig. 9) whose physiognomic features are compatible with given craniometrical features. As a result of a search

Fig. 9. Samples of PPD records.
through *PPD*, we could have a set of physiognomic elements which can guide the refinement of the reconstruction.

### 3.11. Final reconstruction and rendering

The final step is to locally modify the mesh produced in step 3.9, trying to integrate the facial features of ancient Pompeians, as resulting from the previous search. We used a non-linear free-form deformation applied to a vertex selection based on distance from landmarks to properly deform the areas corresponding to eyes, lips and nose. We also tried to generate a digital reconstruction of haircut and shave, because these physiognomic elements, although totally fictitious, help to better visualize the subject as it more probably was. Haircut and facial hair have been applied and oriented using a specific modelling tool. After modelling phase is over we can fine tune the materials properties and then produce the final renderings (see Fig. 10) of the reconstructed head in high resolution.

### 4. Discussion

The methodology presented above actually integrates some of the features typical of the classic reconstructive approaches listed in Section 2, trying to maximize their results specially for archaeological applications.
In fact the warping technique is common to other computerized methods, as it is the use of a “reference” facial mesh to be deformed to fit the found skull, or the positioning of a set of landmarks on the bone remaining to guide the warping.

Nevertheless this methodology differs substantially from the other ones in the following fundamental aspects:

- The building of a custom CD based on the anthropological hypothesis that individuals with similar physiognomic and craniometrical features can still be present in the same area in which the remains were found.
- The selection of a reference candidate through a search for craniometrical similarities in the CD and not just based on a generic race/gender criteria.
- The modelling of a 3D facial mesh by actual (photo, CT or 3D scan) data of the selected (living) reference candidate, and not by average soft tissue depths collected following a generic race/gender criteria and applied to the dry skull.
- The warping technique applied to the mesh with highest CSS to improve the reconstruction, instead of using it as the main tool to conform a generic facial mesh to the found skull.
- The use of PPD to refine the reconstruction adding compatible physiognomic elements (nose, eyes, lips) often missing with other approaches.

These peculiarities lead to a precise applicative range for FACES, with advantages and limits respect to other methods presented.

FACES works best on a complete skull, but even in the case of missing mandible it can still produce interesting results, using the remaining craniometrical measurements to search a similar individual in the CD, thus leading to a complete (even if less reliable) reconstruction.

Another critical point about “warping methods” mentioned in Section 2 is the reference face mesh used, because its physiognomic features affect the final result independently from the correctness of soft tissue depth in the discrete set of landmarks involved in the process. The basic classification for races (Caucasian, Afro, Asian, etc.), sex and build (fat, normal or thin) is often too generic to accurately reproduce the aspect of specific ethnic groups.

FACES, based on the custom built CD containing records of anthropologically compatible individuals, uses as a reference mesh the 3D face model of the most similar individual in the database, thus minimizing the amount of interpolation between the landmarks and leading to a more accurate reconstruction.

Finally, after the landmark based mesh warping is applied, the resulting reconstructed face does not include elements such as nose, lips, eyes, ears or hairs, which cannot be derived from soft tissues statistics, so, as proposed in [1], it is necessary to manually draw them onto a rendered front or side view of the head to obtain a complete identikit.

FACES relies on the PPD to search anthropologically compatible facial features and to apply them on the reconstructed face by local deformations of mesh control points. Even if these added elements still remain fictitious, they could be very useful to visualize the possible aspect/s of the found subject. On the other side, the use of CD and PPD could be a limit to the application of this technique or to the reliability
of its results, if an appropriate radiological/photographic survey on a population anthropologically similar to the subject to be reconstructed could not be available.

We summarize the advantages of the various facial reconstruction methodologies in the following list:

- **Quick/simple**, referring to a method that quickly leads to a result with simple or no technology.
- **3D output**, referring to a method capable to generate a 3D reconstruction of the face.
- **Not subjective**, referring to a method not based on an artistic approach to the reconstruction.
- **Missing mandible**, referring to a method able to work and to produce acceptable results even in the case of absence of the mandible.
- **Cadaver remains**, referring to a method suitable for reconstruction of identity from cadaver remains.
- **Forensic applications**, referring to a method suitable for facial reconstruction to be used for forensic purposes.
- **Archaeological applications**, referring to a method that leads to valid results for archaeological and anthropological studies.
- **Maxillo-facial reconstructions**, referring to a method suitable for surgical reconstruction and simulation.

In Table 3 is showed a comparison between FACES and the main reconstructive methodologies.

### Table 3
Summary table of main facial reconstruction methodologies

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5. Conclusion

Facial reconstruction techniques have a long tradition both in forensic and archaeological fields, but, as long as anthropological studies and information technology help us to better identify and visualize a feasible reconstruction of an individual, given its skull, we have to remark that there is no way to exactly replace
lost data. The approach presented in this paper can considerably enhance the likeness of the reconstructed face to the anthropological features of the ethnic group, which found skull belonged to, but requires correctly built $CD$ and $PPD$ to achieve optimal results.

Future developments of this method will try to use as reference not only the record with the highest $CSS$ found searching through $CD$, but a set of records whose $CSS$ is above or equal to a previously defined threshold. By averaging the mesh relative to each selected record, the resulting face could be a better candidate for the next steps of reconstruction, with probably a lower influence of random physiognomic features than in the case of a single best match.

Acknowledgements

This work was supported in part by the Regional Council of Campania. We would like to thank Prof. F.S. Sasso of Second University of Naples, Diagnostic Imaging, Emergency Radiology and Radiotherapy Department, Dr. M. Gargiulo of Centro Studi Gargiulo in Salerno, and Dr. G. Sabatino for their precious help in the data acquisition phase.

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