Novel Hybrid Teleophthalmology: Technological Case for Oculofacial Surgery

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Abstract—**Telemedicine has emerged as a promising mode of healthcare delivery, especially, in remote areas. In this regard, healthcare providers often follow a multi-tier pyramidal model. Typically, at the bottom of the pyramid are the primary healthcare centers, located in remote areas, which offer basic imaging and recording of vital signals, as well as preliminary diagnosis and treatment. The higher layers of the pyramid consist of secondary and tertiary centers, which provide advanced diagnosis, treatment, surgical care as well as research. In this paper, we focus on teleophthalmology and propose to enhance it by integrating a 3D imaging system into existing multi-tier eyecare. In particular, we present a patient-friendly multiple-camera-based system for facial image acquisition and 3D reconstruction. The proposed system is built using off-the-shelf components, and is easy-to-operate with minimal training. Consequently, our system is suitable for deployment in the primary or secondary healthcare centers. Importantly, it allows the flexibility of performing imaging at a primary healthcare center, and the tasks of 3D reconstruction, visualization and quantification at the tertiary center. Indeed, we envisage a novel hybrid teleopthalmology framework, where diagnosis and various pre-operative steps as well as post-operative followups can remotely be performed on the patient, while s/he needs to undertake significant travel only for the actual surgery. Such eyecare framework is expected to lower the cost and other burdens on remotely located subjects. In emergency situations such as facial trauma, our framework could be particularly effective in reducing the time (and cost) of oculofacial procedures. As a step towards realizing the proposed system, in this paper we present preliminary results of 3D face reconstruction and discuss teleophthalmological implications.**

Index Terms—**Teleophthalmology, Multicamera image acquisition, 3D reconstruction, Oculofacial surgery, Surgical planning**

I. INTRODUCTION

Patient-centric healthcare enables rapid recovery from and even prevention of health disorders. Scarcity of medical and allied resources hinders achieving this goal [1]. In general, healthcare services in urban areas are often burdened due to low doctor-to-patient ratio, prohibitively high costs, large waiting times and other issues. On the other hand, underdeveloped remote areas face a different set of challenges such as poor infrastructure (e.g. road, electricity and medical facilities), unavailability of trained medical professionals and lack of awareness among patients [2]. As a result, many life-threatening communicable and non-communicable disorders remain untreated.

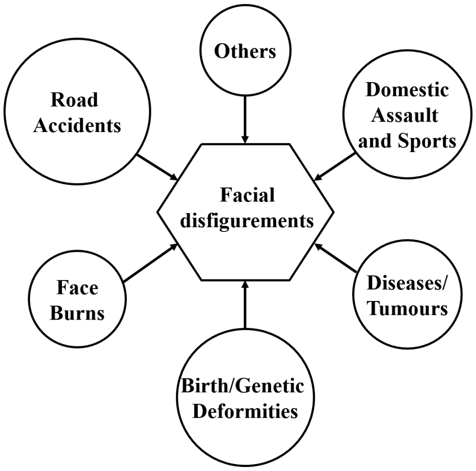

Fig. 1: Causes of facial disfigurements. The size of the circle is indicative of the prevalence of the respective cause.

Telemedicine promises an attractive solution in both the aforementioned scenarios [2]. In addition to curative care, preventive measures can also be taken via telemedicine. Pertaining to eyecare, the telemedicine paradigm is known as teleophthalmology. In comparison with various practices in ophthalmology, the sub-specialty of oculofacial surgeries has not been incorporated well into the teleophthalmology, due to its interdisciplinary and complex nature [4]. In this paper, we propose a facial surface imaging platform and discuss its potential vis-à-vis existing teleophthalmology framework. We aim to facilitate pre-operative planning and post-operative assessment of oculofacial surgeries, but not the surgery itself. As shown in Figure 1, such surgeries, which can be of reconstructive and/or cosmetic nature, are necessary to treat various facial disfigurements. Various etiological studies have shown that road accidents remains a leading cause of such disfigurements, particularly in the developing countries [5]–[7]. Some of the other prevalent causes include domestic assaults, sports injuries, deformities during birth, tumors, face burns etc. The aforementioned etiological surveys collected their data from specific hospitals over a period of time. Collating such quantitative information across these studies is difficult. Therefore, in Figure 1, the sizes of the circles roughly

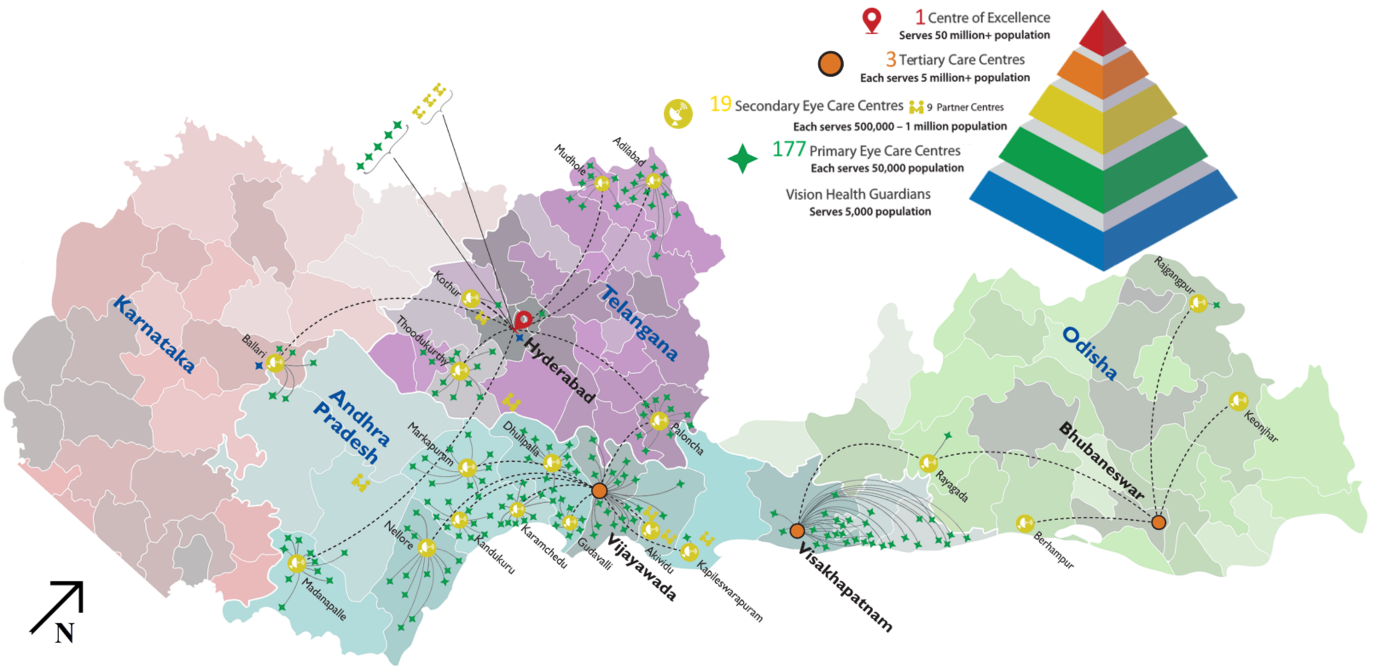

Fig. 2: The L. V. Prasad Eye Care Network. Courtesy: L. V. Prasad Eye Institute, Hyderabad [3].

represent of the prevalence of the respective causes, and not the exact percentage.

In this paper, we focus on oculofacial procedures, addressed within an existing teleopthalmology framework, depicted as a pyramid structure in Figure 2. Specifically, the map shows the eyecare network of L. V. Prasad Eye Institute, Hyderabad, India, spread across the following states of India: Andhra Pradesh, Karnataka, Orissa and Telangana. Each state is differently coloured with constituent districts presented in lighter shades indicating lower per capita income state [8]–[11]. Since the data were not collected for the same year across the states, one can only compare the districts within a state based on the hues. In the following, we describe the structure of such eyecare network [3].

Typically, at the base of the pyramid are vision guardians that represent community involvement. Vision centers form the next level and serve the primary eye health needs of the community. Secondary eyecare centers can diagnose the complete range of ophthalmological diseases and offer high quality surgical care. Tertiary centres provide a comprehensive range of services and also serve as training centres to the secondary centres. At the appex, centers of excellence treat complex diseases, and provide training in subspecialties and rehabilitation [3].

The primary care centres at the bottom of the teleopthalmology pyramid usually involve basic imaging equipment, often at a remote establishment. Images acquired at such centers are sent to the secondary or tertiary centers where doctors make a judgment based on visual inspection and devise a treatment plan. At the remote primary center, the subjects are treated according to the plan and follow-up visits are made. Such an arrangement is useful for regular diagnosis as well as pre-operative checkups for planned surgeries. This conventional paradigm is depicted in Figure 3(a).

In emergency situations such as facial trauma, the subject needs to travel to a nearby city where reconstructive facial surgery is performed. Usually, as depicted in Figure 3(b), the subject needs to travel for a few hours (Δ_T), undergo some initial checkups, some of which aid the preparation of surgical material such as 3D moulds (Δ_M), wait until the required surgery is planned by experts (Δ_P), and then finally get operated (Δ_S). Furthermore, the subject is often required to stay in the hospital for post-operative assessment. Depending upon the financial capability of the subject, the time[1] and money spent in this whole process could be devastating for him/her. Even if the surgery is paid for, the time lost in the process directly translates to lost income – a catastrophic situation if the subject's earning comes from daily or weekly wages. Furthermore, it may be difficult to gather all the required experts multiple times during various stages of the proposed surgery. Clearly, a primary healthcare center cannot help in such a situation.

In this backdrop, we propose a hybrid teleophthalmology paradigm. In this proposal, the subject under emergency situation still has to travel to the closest secondary or tertiary center for surgery. However, certain amount of time in pre- and post-operative phases of surgery could be saved if the primary centers are equipped with an imaging system that can capture oculofacial information. As depicted in Figure 3(c), a subject under emergency situation is taken to a primary center

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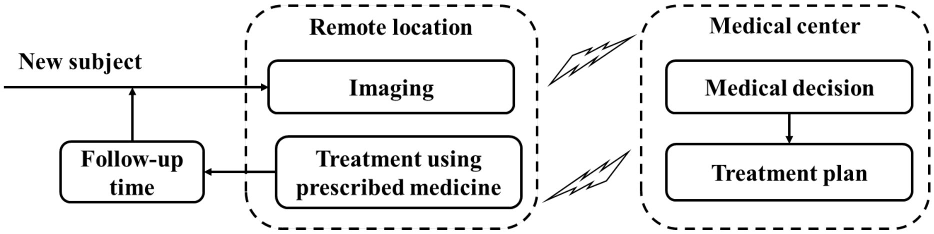
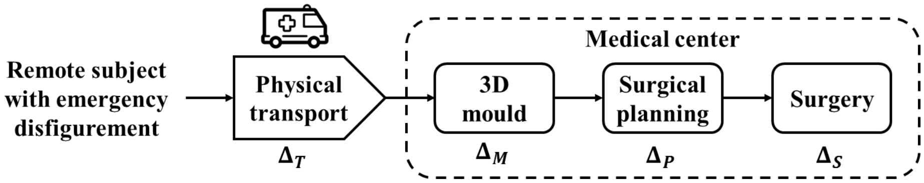
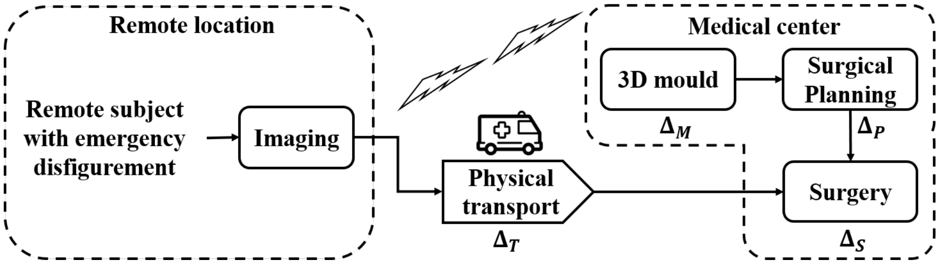
[1] Total time spent = $\Delta_T + \Delta_M + \Delta_P + \Delta_S$



(a) Conventional teleophthalmology.



(b) An emergency scenario.



(c) Proposed hybrid teleophthalmology paradigm.

Fig. 3: Teleophthalmology paradigms.

where facial images are acquired. While the subject travels to the nearby city for surgery, the information acquired earlier can be transmitted to the hospital. Using those images, key facial measurements can be made, as well as a 3D model facial model can be reconstructed which is instrumental in planning the surgery. In this way, the planning phase of the surgery can start even before the subject reaches the hospital, saving a considerable amount of time[2]. Furthermore, during the post-operative phase and further examinations, the subject can just visit the primary center capable of acquiring facial information. The imaging system to be deployed at the remote primary centers needs to meet certain requirements. From the clinical perspective, it is necessary that the subject under trauma is admitted to hospital as soon as possible. Therefore, the image acquisition operation should be instantaneous. Even in absence of trauma, a human being cannot remain stable for an extended period of time required by conventional face scanning systems. Furthermore, due to the trauma and/or personal preferences, taking measurements of facial features using an instrument that requires physical contact with the skin is often not suitable. From the perspective of regenerative surgery, the measurements should be accurate and retain the scale of the human face. Finally, the imaging system, unlike the legacy surface imaging equipment, should be easy to deploy and operate after a minimal training, owing to lack of trained professionals and other resources observed at primary healthcare centers. In summary, the following attributes, depicted in Figure 4, are desirable in an oculofacial measurement platform: (i) instantaneous data acquisition; (ii) non-contact procedure; (iii) accurate true-to-scale measurement; (iv) flexibility of deployment; and (v) ease of use. The first two attributes ensure subject comfort, the third one assures measurement fidelity, the fourth one facilitates convenient operation, while the fifth one allows one to employ operators without extensive training. In this paper, we address a specific problem of 3D reconstruction of the human face to facilitate pre-operative surgical planning and post-operative assessment [12]. Note that our method does not intend to facilitate the surgical procedure itself.

In recent years, various 3D surface imaging technologies have been suggested for oculofacial surgical planning. Such systems are broadly classified as laser-based and optics-based systems [14]. Typical laser-based systems acquire 3D facial surface data on a band-by-band basis by projecting a line laser onto the subject's face and recording the time of flight of the laser. Albeit providing highly accurate 3D data, such systems require the subject to remain still for a considerably long period, and therefore remain inapt for conscious subjects, especially children. Movement increases the likelihood of distortion, noise, and voids in the scanned image.

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[2] If the planning phase successfully completes before the subject arrives to the hospital, the total time spent = $\Delta_T + \Delta_S$

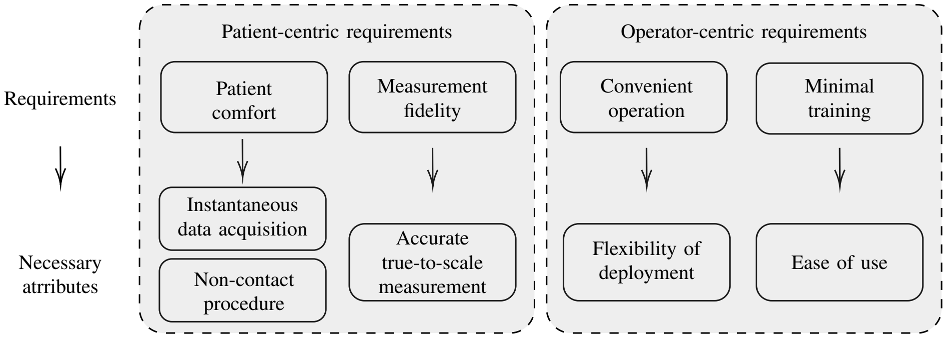


Fig. 4: Key requirements and necessary attributes of a facial data acquisition system [13].

Fig. 5: An instance of the facial surface imaging platform used in this paper. 'SL' and 'SR' cameras form a stereo pair. 'Mi' indicates i^{th} monocular camera.

The optics-based systems enable faster scanning. They primarily involve stereo photogrammetric techniques and/or structured light. The former ones use calibrated stereo camera pair(s). 3D information is obtained through triangulation of features across stereo images. Although instantaneous, such systems face two limitations (i) the pre-calibrated stereo cameras make the setup non-adaptive to ambient changes, and (ii) detecting and matching features across extra-ocular facial images is difficult and results in sparse 3D reconstruction. To this end, a sequence of structured light patterns such as grids and/or dots are projected onto the face as features. The deviation in patterns from the reference patterns (precalibrated) provides required 3D information. However, such sequential image capturing unduly burdens the subjects by requiring them to remain still for several seconds.

In this paper, we present a multicamera-based facial data acquisition system that attempts to meet the aforementioned desired attributes (Fig. 4), and discuss its suitability for the proposed hybrid teleopthalmology paradigm. Our work builds upon the earlier works of Vupparaboina *et al.* on unambiguous Euclidean calibration of a camera network [15], [16], dense 3D reconstruction of a 3D head model [13], [17] and a preliminary sparse 3D reconstruction of a real human face [18] from its multiple 2D views. The rest of this paper is organized as follows: Section II elaborates the image acquisition setup and briefs the 3D reconstruction method. The results of the 3D reconstruction of a real human face from its multiple 2D views are discussed in Section III. Section IV discusses about the broader impact of this work and concludes the paper.

II. METHODOLOGY

In this section, we elaborate the image acquisition setup and the steps followed to acquire multiple 2D views of a human test subject. We briefly explain our method of achieving 3D reconstruction from multiple views. A detailed description of this method, including the theoretical underpinnings, is provided in the earlier works of Vupparaboina *et al.* [13], [15]–[17].

A. *Image acquisition*

The image acquisition system comprises of a network of six Internet protocol (IP) cameras [19], two independent projectors [20] and a desktop computer which controls the cameras via an Ethernet switch [21]. As shown in Fig. 5, two of the six cameras were arranged as a stereo pair on an aluminum mount, with a baseline length of 45mm. The stereo pair was located between two monocular cameras on the left and two monocular cameras on the right. The six cameras arranged in this manner are identified as M1, M2, SL, SR, M3 and M4, respectively.

The projectors were used to project a fixed structured light pattern on the face in order to create features to be tracked across the multiple images of the human face. The structured-light pattern largely determines the density of the reconstructed 3D point cloud. In contrast to the conventional sequence of structured light patterns containing black and white stripes, we used a colored structured light pattern. The pattern contained square patches of selected colors. Each patch had a marker at its center to facilitate dense matching. The markers serve as feature points and corners of patches provide feature descriptors. In an earlier work by Vupparaboina *et al.*, the structured light pattern projected from the front was deformed at the sides (cheeks) of the face, posing difficulties in establishing point correspondences [13]. Therefore, in this work, we projected the same structured light pattern from two projectors whose optical axes approximately converged at the centre of the face.

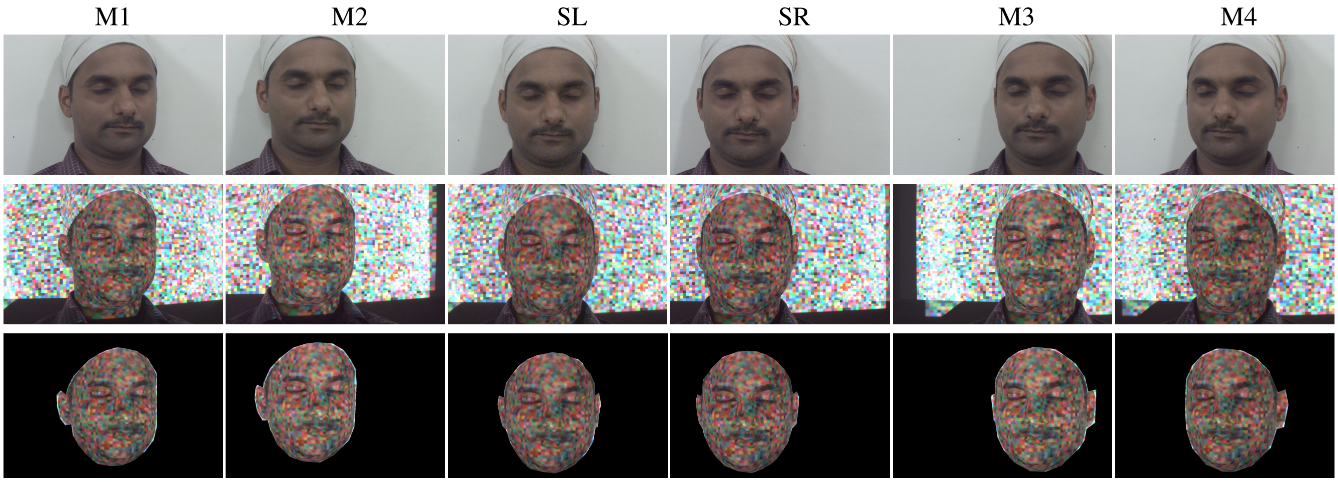
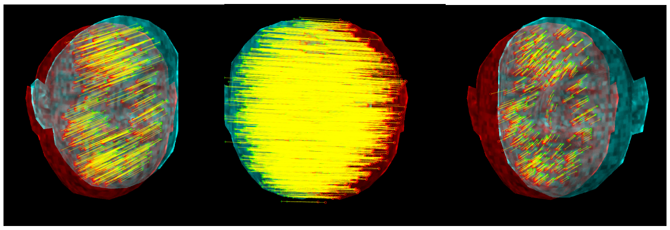


Fig. 6: Multiple 2D views of the human face. Top row: Images captured for texture information. Middle row: Images with structured light pattern projected. Bottom row: Images with only the region-of-interest retained.



(a) M1 $\longleftrightarrow$ SL (b) SL $\longleftrightarrow$ SR (c) SL $\longleftrightarrow$ M4

Fig. 7: Point correspondence between a few camera pairs.

Then, one image per camera was captured in a sequential manner using software triggering. Although sequential, the image acquisition process was found to be nearly instantaneous. The camera settings, optimized to maximize the image quality given the indoor lighting conditions, were made identical across the cameras.

As shown in Fig. 5, the image acquisition system was arranged in a laboratory whose dimensions were 11×19.25 sq. ft. However, the setup itself occupied a floor area of 7×7 sq. ft. The subject was seated on a stable plastic chair. The distance between the center of the stereo camera and the approximate centre point of the chair was 2 ft. The images were acquired with two lighting conditions for two specific purposes. First, the texture information was acquired with two fluorescent tube lights turned on. Next, with the tube lights turned off, the structured light patterns were projected and another set of six images were captured in order to track common features across the viewpoints. The entire operation took a few seconds to complete.

A set of six images of a human test subject captured in this manner is shown in Figure 6. The top row depicts texture information, the middle row shows images acquired with structured light patterns projected onto the face, and the third row shows masked images in which only the regions of interest (ROI) are retained. The masking was achieved using morphological operations [22]. Extracting ROIs facilitates robust point correspondence across the images. A set of feature point correspondences, common across all or at least subsets of consecutive cameras, is necessary to achieve camera calibration [15]. We provide an overview of the 3D reconstruction method used in this paper in the following.

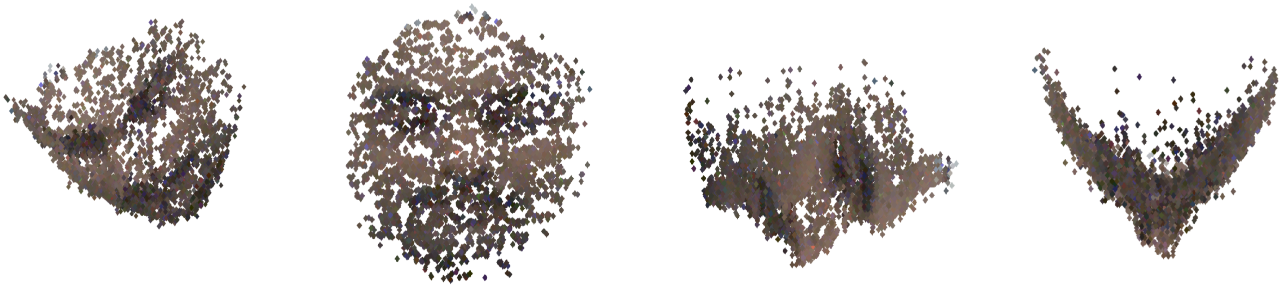
B. 3D reconstruction

Figure 7(a), (b) and (c) depict point correspondences between the following pairs of cameras, respectively: (i) M1 – SL, (ii) SL – SR and (iii) SL – M4. The number of point correspondences reduces with the increasing distance between cameras. Between the cameras of the stereo pair, we obtained a large number of point correspondence, whereas between the SL camera and the M4 camera, the point correspondence was sparsest. With the point correspondences obtained, we used a 3D reconstruction method proposed by Vupparaboina *et al.* which involves iterative minimization of reprojection errors. In the process, the method estimates intrinsic (e.g. focal length) and extrinsic (pose) parameters of the camera as well as 3D co-ordinates of the feature points.

III. RESULTS AND DISCUSSION

We now provide results of the 3D reconstruction of human face. Figure 8 shows several views of the reconstructed point cloud, visualized in MATLAB. A surface fitted on this point cloud is shown in Figure 9. The screened Poisson surface reconstruction method [23], available in Meshlab software [24], was used to generate the surface.

Table I compares the reconstructed point cloud with the real human face using a few key facial measurements. The measurements of the 3D point cloud were distances, measured in MATLAB, between two extreme points of the selected facial feature. Since the reconstructed point cloud was sparse and the



(a) 3D view. (b) Front view. (c) Side view. (d) Top view.

Fig. 8: 3D point cloud with texture information.

points were selected manually, the measurements could have an error. Similarly, for measurements on the actual face, we attempted best possible selection of the two extreme points between which the distances were measured. These results show that our preliminary 3D reconstruction is accurate and true-to-scale.

While we report our experiments and results for one human test subject in this paper, the arrangement was found to be suitable for multiple test subjects of similar physical characteristics such as height and size of their head. Thus, one need not necessarily adjust the pose (extrinsic parameters) and the focal lengths (intrinsic parameters) of the cameras for every test subject. Furthermore, the depth-of-field of cameras used in this work was found to be sufficient so that the entire face was in focus. In this backdrop, we believe that the required array of cameras can also be built using inexpensive off-the-shelf USB cameras. If one manages to create reliable stereo pairs using such cameras and achieve near-instantaneous acquisition via a USB hub, the imaging setup can potentially be stored and carried in a backpack. The setup can be supplemented with a look-up table of recommended camera heights and camera-to-subject distances so that the face to be acquired remains focused and within the field-of-view of the cameras.

Although not a current focus of our research, we briefly discuss the usability of proposed system in the context of mobile healthcare. The total floor area occupied by our image acquisition system was 7 × 7 sq. ft. Interestingly, the required floor area can be easily managed inside a bus. Such a possibility complements the existing efforts towards mobile eyecare. In several resource-constrained situations where setting up primary healthcare centers is not possible, mobile eyecare solutions have been proposed. In particular, a few trained personnel can travel to remote villages using a vehicle such as a bus equipped with basic equipment to perform preliminary checkups. The proposed image acquisition system can potentially be accommodated in such a vehicle. This approach, in the least, solves the issue of unavailability of reliable electricity and poor lighting conditions in such remote areas.

Although promising, the success of the aforementioned proposals relies on the robustness of the 3D reconstruction algorithm against the imperfections in the acquisition setup and in the acquired images. First, the ad hoc stereo pair created from two discrete cameras may not exhibit the ideal characteristics such as parallel optical axes and precisely known baseline length. Characterization of such imperfections has been discussed in several works such as Huang *et al.* [25] and Tamboli *et al.* [26]. Further, projection of bright structured light patterns, although for very short period, could be uncomfortable for some subjects. To this end, one can consider using infrared (IR) structured light patterns along with IR cameras. To the best of our knowledge, such a multicamera system containing both conventional and IR cameras remains unexplored in terms of usability, cost and maintenance requirements with respect to the application of 3D reconstruction of real human face. Several face scanning systems are available which contain at least one IR projector, one IR camera and one conventional camera. However, such systems, as alluded earlier, put an undue burden on the test subjects.

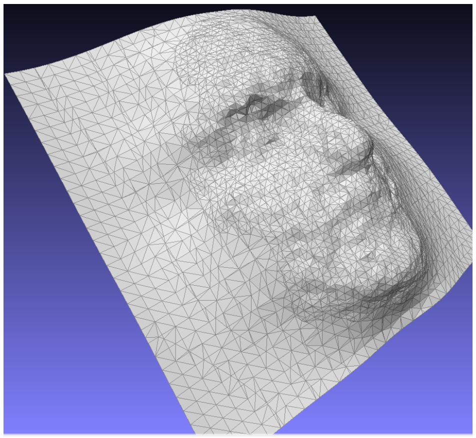


Fig. 9: 3D mesh visualized in Meshlab.

Many commercial 3D face reconstruction systems exist that offer practical results albeit requiring some prior knowledge [27], access to range-scanned 3D point clouds of faces [28], stereoscopic camera combined with infrared projection and sensing where either the subject or the camera

TABLE I: Key facial measurements

Facial measurement	3D point cloud (mm)	Original face (mm)	error	
			mm	%
Lip width	55.5	55	0.5	0.9
Nose length	48.8	50	-1.2	-2.46
Nose height	15.2	15	0.2	1.32
Eye socket length	38.8	38	0.8	2.11
Nose to upper lips	29.24	30	-0.76	-2.56
X-span	153	155	-2	-1.31
Y-span	162.5	160	2.5	1.54
Z-span	71	68	3	4.23

needs to be moved [29] etc. It is important to note that the proposed system aims to minimize burden on the subject and does not use any prior information. In the future, we shall use some of the techniques used in aforementioned works, with the primary aim of convenient and instantaneous acquisition.

IV. OUTLOOK

In this paper, we presented preliminary results on true-to-scale 3D reconstruction of a human face using its multiple 2D perspectives. The multiple images were acquired using a network six cameras, of which two cameras formed a stereo pair. The stereo pair ensures true-to-scale 3D reconstruction. Our image acquisition system meets the key patient-centric and operator-friendly requirements of such data acquisition systems, discussed earlier (Fig. 4. The reconstructed 3D point cloud preserves the scale. Consequently, dimensions of certain key facial features, measured on the reconstructed point cloud and the real human face of the test subject, are found to be very close.

Such an easy-to-use 3D face acquisition system is useful in a variety of situations beyond teleophthalmology. For example, many such inexpensive systems can be used to create a nationwide database of 3D faces of citizens. Such a database would help in law enforcement.

In the future, we shall test our facial image acquisition and 3D reconstruction method under various lighting conditions, multiple test subjects and consumer-grade cameras etc. Further, we plan to fit parametric surface on the reconstructed 3D point clouds. For individual facial features such as nose, cheeks, forehead, etc., we expect the model parameters to be similar across a group of population. Knowledge of such parameters can aid research in anthropology.

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