Experimental Investigation of Photogrammetric Surface Analysis of Heat Shield Materials during Plasma Wind Tunnel Testing

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The paper presents first results of an experimental analysis of surface recession using advanced photogrammetric tools. Based on image pairs acquired with two DSLR cameras, classical photogrammetry has been tried, but pixelwise image analysis with corresponding matching algorithms show much better results ans higher stability to image noise and radiation and reflection issues. A combination of open source tools for the analysis of camera positions and focal points, pixel matching analysis, and pixel cloud comparing, allows the recession to be measured with very high local resolution of $20\,\mu$m of a 2D surface. The approach is analysed within this study with respect to window disturbance and experimental setup constraints. A first plasma wind tunnel experiment shows the applicability and an analysis of a central spot is comparable to laser recession measurements.

I. Introduction

Experimental investigation of the thermochemical performance of heat shield materials is usually conducted in plasma wind tunnels [1, 3]. State of the art diagnostic tools concentrate on the measurement of surface temperatures, in-depth temperatures using thermocouples, and spectroscopic diagnostics to analyse the plasma layer in front of the tested materials [?, 2].

A further crucial parameter to judge the performance of candidate materials is the surface change, i.e. recession of the surface and its deformation or shape change [7]. In particular for ablative thermal protection systems, where surface recession is an essential feature of the thermal protection, the design and layout of the TPS depends on the material's geometrical behavior (see e.g. Milos et al. and Park for the difference in analysis of the Galileo heat shield performance [4, 5]). Furthermore, the rate of ablation even of very simple materials varies with time [7]. Therefore, a diagnostic tool is needed to observe the material's recession as a function of time. Finally, knowing the recession would allow to analyse its influence on the boundary layer. Pyrolysis gases lead to a cooling effect in the boundary layer and solid particles ablating can have a blocking effect to heat flux [5]. Knowing the recession can give first insight to the amount of material additionally present in the boundary layer.

Different approaches to measure the surface recession from embedded sensors have been published. The most recent development is the recession sensor developed for the Mars Science Laboratory (MSL) [?, ?].

In ground testing environments, surface recession and surface changes can be observed using optical methods. Very simple approaches are based on the observation of laser spots on the surface that change its position when the material recesses [?]. This technology is also investigated by the authors in the plasma wind tunnels at IRS.

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However, the main drawback of these systems is that the shape change is not observed due to the point measurement. Improvements could be made by using laser sheets or fast moving laser spots, but a much simpler approach is the direct observation of the surface and the application of photogrammetric tools to determine the three-dimensional surface geometry. This technology has been successfully demonstrated by Schairer et al. for arcjet tests at NASA Ames using CCD video cameras [6]. This system allows a maximum frame rate of 16 Hz and an accuracy of 0.3 mm.

The approach presented in this paper follows photogrammetric image analysis. Basically, two different open source software tools have been used to analyse simultaneously acquired photographies of the recessing surface. Modern photogrammetric software tools are based on a pixelwise analysis allowing a high geometrical resolution and a comparably high accuracy. In a first experimental part the principle feasibility of the approach was verified under lab conditions at room temperature with focussing on the equipment used and the types of materials to be tested. Two digital single lens reflex (DSLR) cameras were adapted for plasma wind tunnel purposes using fixed focal length (300mm or 420mm) lenses. The plasma radiation has been analysed with respect to photographic imaging of heated samples.

II. Methodology

The methodology presented here is the result of an extensive study of different hard- and software approaches. First, a commercially available photogrammetric analysis program named Aramis from GOM mbH has been applied [?]. First promising results were investigated in more detail in a laboratory setup in order to analyse the constraints of the program [?]. The main drawback of the commercial software was insufficient user information resulting in very problematic calibration issues. In cooperation with the Institute of Photogrammetry of the University of Stuttgart, an in-house code named Australis which uses similar numerical tools for the calibration as Aramis does, showed that the main problem arises from the long focal lengths for comparably small objects and disadvantageous geometrical setup, i.e. view angle [?].

Meanwhile, there are many new developments for the calculation of three-dimensional sceneries using multiple 2D images. The invention of those tools comes with the three-dimensional analysis of aerial views and three-dimensional city maps, e.g. google street view citeFukuhara....

The approach that we are following in this paper is based on three different open source software solutions which will be described briefly in the following subsections [?]. The starting point are two images taken from the same situation with the two cameras (see section III for experimental details).

A. Bundler

The images taken with the two cameras are first analyzed with a software named Bundler [?]. This software allows to reconstruct several significant points in different images. Originally, it has been programmed to reconstruct the same scene from several viewpoints particularly interesting for applications with image searches on the internet [?].

In the present application, the software is used to analyse camera position and focal length. Unfortunately, the program does not allow to identify changes in any dimension of an image. Therefore it can not be used to measure the recession, i.e. the movement of a significant image pixel in on particular direction.

Bundler uses a pinhole camera model to position the camera with respect to the taken images

The Bundler software is restricted to 5 Megapixels. The images taken are usually 16 Megapixels. The resolution is reduced mainly by reducing the size of the images since only a small part of the picture contains the observed recessing sample.

B. Dense Matching and Cloud Compare

Using the so–called Dense Matching method together with the visualization software Cloud compare, the acquired photographies are analysed. Dense Matching has been developed at the Institute of Photogrammetry of the University of Stuttgart cite. Basically it uses the same approach as Bundler does. It reconstructs a 3D surfaces from at least two images identifying significant features in two or more images. Corresponding pixels between images are identified and possible positional changes of identified pixels from one pair of images to the next are analysed using the visualization software Cloud Compare.

The dense image matching step determines a connection for every pixel in the image leading to a dense point cloud. A pixel $\vec{p} = [p_x p_y]^T$ with the intensity I_{lp} in the left image is suspected a correspondence to a pixel $\vec{q}$ in the right image with intensity I_{rq}. The pixel q is

$$q = e_{lr}(\vec{p}, d) \tag{1}$$

where e_{rm} is the epipolarline in the matching right image of the pixel $\vec{p}$ in the left image. d is the disparity between $\vec{p}$ and $\vec{q}$. In the present case with rectangular images e_{lr} becomes $e_{lr}(p\vec{p}, d) = [p_x - d\,P_y]^T$. In order to identify matching pixels, a matching cost function is defined [**?**]. It is based on the so–called *Mutual Information* which can be calculated from the entropy of the corresponding images. The entropy is defined by the probability distribution function of the pixel of interest. Geometrically, the matching right image has to be warped with a disparity D to become the base left image. Every pixel has to be treated separately. The unknown D image is searched iteratively with some additional boundaries, e.g. gradient conditions between adjacent pixels. Knowing D means to know the corresponding pixels in both images.

In the more classical photogrammetry calibration images are taken and transformations are calculated for certain corresponding windows. The camera' inner and outer orientation is identified from the calibration images and the most advanced method **... Buendelblockausgleichung ...** is based on those calibrations. These methods are computationally rather expensive, but their main drawback is that these methods do not work at fine structures and discontinuities [**?**].

The drawback of a pixelwise analysis is that the calculation also needs high computing capacity. Furthermore, grey values are not unique in one image, so the connection between pixels from the first to the next image is not unique. Therefore, it uses an approximation of a global smoothness constraint of the observed surface over the image. This reduces the needed computing power and increases the probability for a useful correspondence. Noise can also be reduced with this method. Fig. 1 shows the result of the matching procedure. Both samples have been sprinkled with Keratin to improve the contrast and to assure clear comparable points. The left and right image are plotted next to each other and the lines point on the different features. Since the two images have been acquired at almost the same horizontal level, the lines

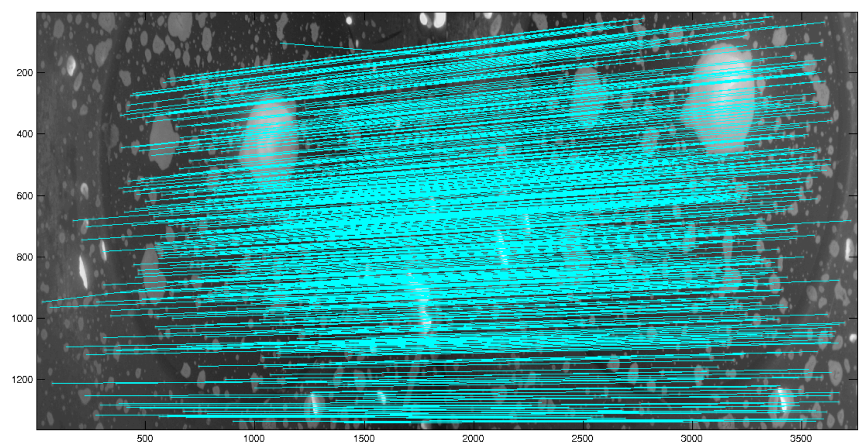

Figure 1. Result of feature matching.

should be almost parallel lines. It can be seen in Fig. 1 that some lines are warped significantly (e.g. the most top line). This indicates that an artificial feature has been identified. The higher the number of those wrong identifications the worse is the following triangulation process. In images with weak surface features, obviously the identification is more difficult. This motivated the investigation of different surfaces of interest in order to judge the performance of this method for recession measurement purposes.

The identified point clouds are analysed using the software CLOUD COMPARE. This is basically a tool to analyse various point clouds. The different image pairs of an experiment are loaded as a 3D point cloud which allows then to analyse possible pixel offsets. Fig. 2 shows the overlay of the first and the last acquired and analysed image pair of an experiment. As can be seen, there is a clear difference between the two images. In order to relate this to a recession, the scaling between pixels and mm has to be determined. One possibility is to use a known distance in one of the images or an image pair is used as a calibration distance.

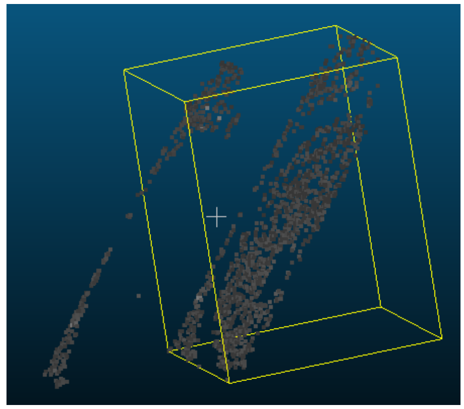

Figure 2. Raw image of two point clouds in Cloud Compare.

Finally, Fig. 3 shows a resulting surface image of the 3D cloud of the probe and the sample within a plasma wind tunnel test.

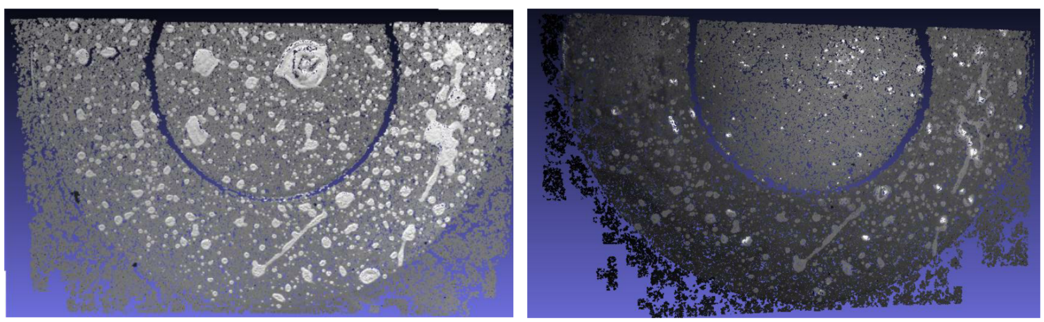

Figure 3. Perspective view of reconstructed point cloud.

III. Experimental Setup

The challenge to mount the photogrammetric setup at the plasma windtunnel facility is the limited access allowing an observation of the probe surface. The material tests within this study have been performed in the plasma wind tunnel PWK1. The probe is mounted on a moving platform inside a vacuum chamber with a diameter of 2 m and a length of 6 m. There are only small optical windows to observe the plasma flow and the probe. Fig 4 shows a photography and a sketch of the setup using two cameras. It has been decided that the best solution is to use the two inclined windows in the front lid of the vacuum chamber. Here, possible reflectivity issues are minimised and a comparably large part along the axial direction of the wind tunnel can be observed. The front lid has to be opened for sample installation, therefore, the camera setup has been mounted on separate tripods. This has the further advantage that vibrations of the vacuum chamber during evacuation do not affect the camera setup.

The images are acquired using two digital single lens reflex (DSLR) cameras of type Canon EOS 60D. Table 1 lists the parameters of the camera setup. Both cameras are released simultaneously radiocontrolled within < 100 ms. For the present investigation of the photogrammetric applicability, only few images were taken at a rate of one image per 30 s, the maximum rate of the camera being 6Hz. Figure 5 shows an example of a material probe in the plasma wind tunnel as seen through the side windows (left). On the right photo, a first photography of an ablation sample is shown. The plasma flow emission becomes fairly week in the visible at very short exposure times which allows an observation of the sample's surface. For the surface photo an f-stop of f/9 at an exposure time of 1/500 s has been set. Note that the bright spot in the center is a laser spot used for laser recession measurements.

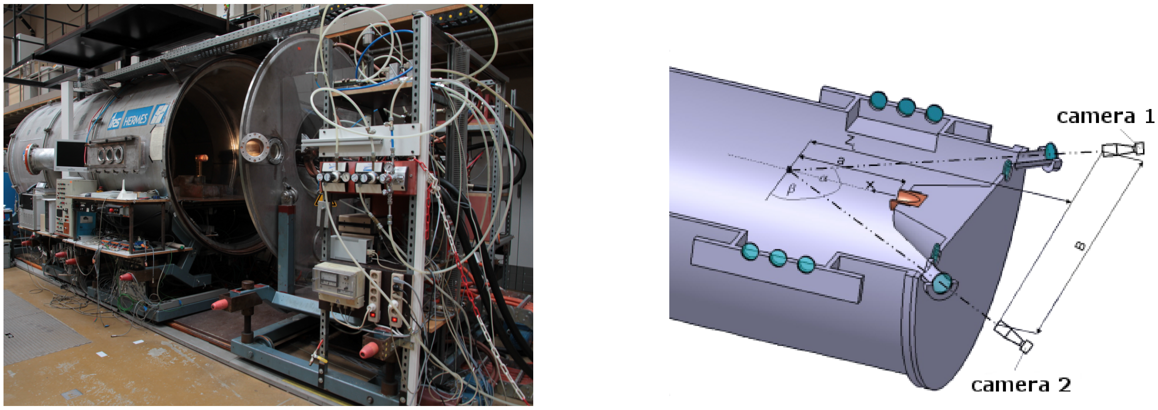

Figure 4. Plasma windtunnel PWK1 (left) and geoemtrical setup for the photogrammetry (right).

Table 1. Camera setup.

camera	Canon EOS 60 D
pixel	5184 x 3456 px^2
chip size	22.3 x 14.9 mm^2
pixel size	4.3 μm
aperture	22
ISO	100
exposure	automatic
focal length	420 mm
color depth	12 bit

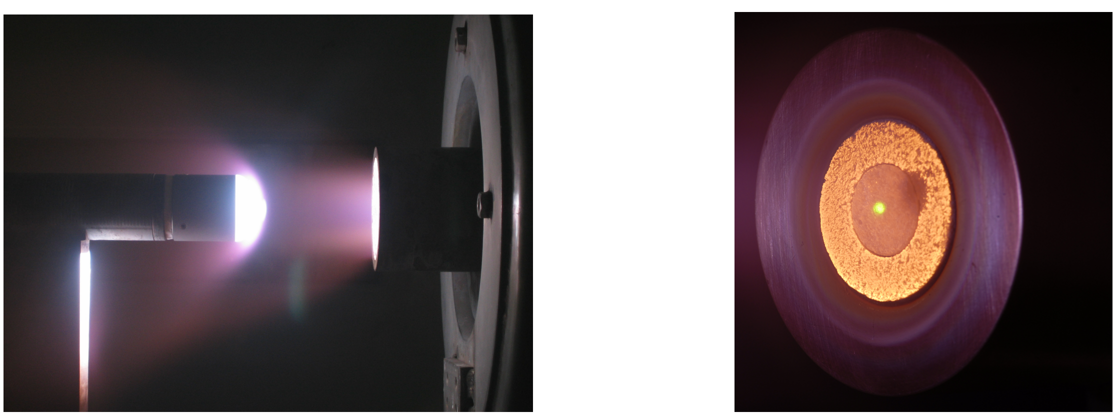

Figure 5. Material probe in the plasma wind tunnel (left) and photography of a material's surface (right).

IV. Results

The results section is divided in three main parts. First, an analysis of the setup's performance concerning observation angle is presented. Then, the analysis of different probe surfaces is presented. Here a generic setup has been used with an oxyacetylene torch for sample heating. The purpose was to investigate whether and how different surface reflectivities and surface structures affect the data analysis. Finally, first plasma wind tunnel testing has been performed and a first recession analysis has been conducted.

A. Setup performance

The camera setup has been installed in the DLR laboratory in order to investigate the problematic access through the chamber windows. As can seen in Fig. 4 the windows do allow a certain view angle β with respect to the probe surface. If the probe is moved towards the generator to increas the heat load, the angle is becoming smaller, thus the photogrammetric approach becomes more complex. Fig. 6 shows the results of different base distances and apertures as an overview. These results have been acquired using the Aramis software. Distances between 870 mm and 3400 mm have been investigated. However, the maximum base distance for Aramis is 1500 mm. The facility, however needs a base distsance of 3200 mm, which indicates the problem of using Aramis.

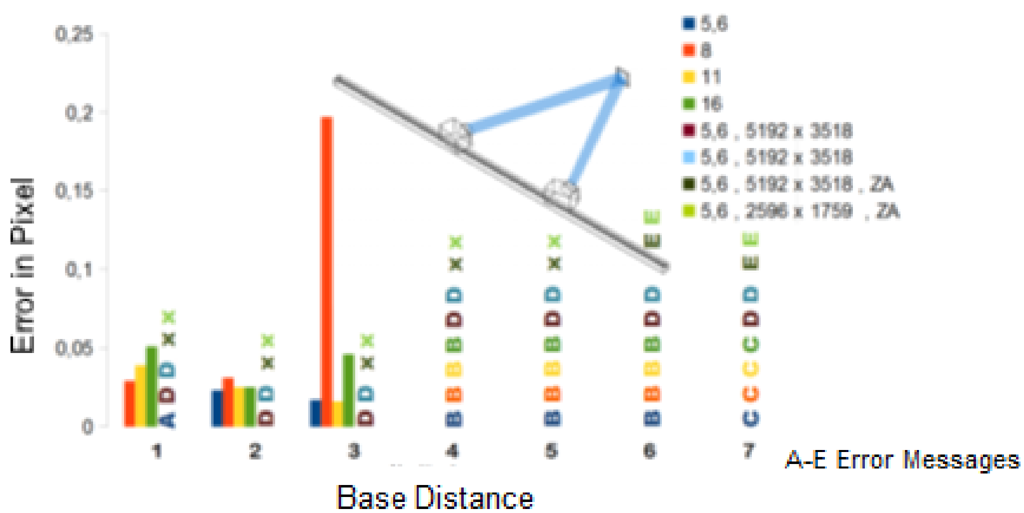

Figure 6. Increasing base distance error when using Aramis) [?].

B. Influence of the vacuum chamber windows

As described, the camera system is mounted outside the vacuum chamber for two main reasons: The camera system is not endangered to be damaged by hot gases and the camera setup can be modified during facility runtime.

The drawback of this setup is that the pictures are taken through the windows of the vacuum chamber. In order to minimize transmission losses, fused silica windows are mounted with high transmission between 200 nm and 900 nm. The cameras have been setup at the Institute of Photogrammetry of the University of Stuttgart in order to measure the difference with respect to recession accuracy for the windows. It has been shown that the window does not affect with respect to transmission (see Fig. 7). However, the reflections at the surfaces of the window do affect the measurements slightly. The most critical issue is a possible change in the setup during measurements. Therefore, the optical path between camera and window should be covered to avoid any random reflections and the camera adjustments have to be fixed with the appropriate set screws to avoid a change in focal length.

Comparing mirror setup similar to the one used by Schairer et al., the accuracy of the present study $20\,\mu$m instead of 0.2 mm .

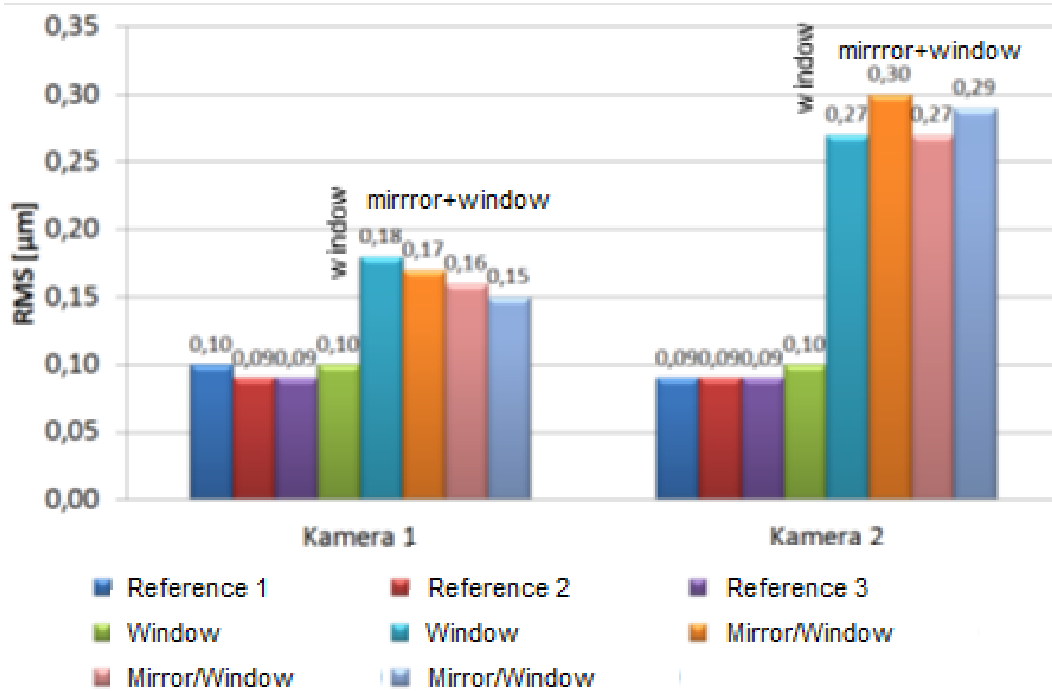

Figure 7. Influence of vacuum chamber windows and possible mirrors.

C. Surface condition and resolution

The data analysis strongly depends on the feature detection possible on the surface of interest. The two taken images have to be compared and therefore descrete features in every image pair are needed. Within th preparation of this approach, four different materials have been considered: pretreated carbon, virgin carbon, porous carbon, and a ceramic matrix composite C/C-SiC. The C/C-SiC material has furthermore a highly reflecting surface. All candidates are shown in Fig. 8. Using the approach with Bundler-Dense

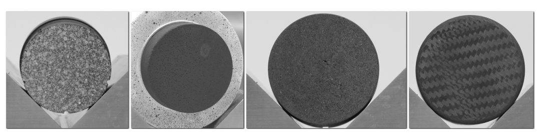

Figure 8. Different surfaces of common heat shield basic materials.

Matching-Could Compare all material surfaces have been identified with high resolution. The higher reflectivity does not affect the number of identified features nor the accuracy of the triangulation. The surface discretization is very high (see Fig. 9). The scale is given in the lower right of the figure. The probe diameter has been 40 mm and there are about 1000 px in lateral direction, thus, there is about 1/400 mm per pixel. This high discretization means that the triangulation allows high accuracy. It can be clearly seen that there is an inhomogeneous recession, although the heat flux affecting the surface can be assumed to be rather constant across the sample surface. The recession is obviously also affected by the probe body and the highest recession is on the lower right side. Evaluating the center spot for different measurements with 300 s shows Fig. 10. The sample has been introduced into the flow at 0 s. The recession seems to reach a constant level after a higher beginning rate. The ablation processes seem to have a higher recession at the beginning. Wernitz et al. also observed a similar behavior when analysing emission spectra of the boundary layer [8]. In order to interpret further the resulting recession from the photogrammetric setup, Fig. 11 shows the recession of a similar sample measured with the laser pointing setup. The focused laser spot was about 5 mm in diameter. Therefore, the analysed recession is a mean value of a spot around the center pixel of Fig. 10. Furthermore, the heat flux was significantly higher. However, the basic result is similar. After the insertion of the probe recession rate is higher than the recession values after 5 s. The accuracy of the laser

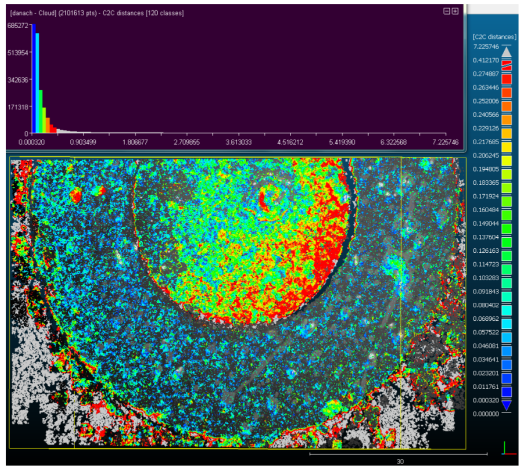

Figure 9. Resulting pixel cloud from photogrammetric measurement.

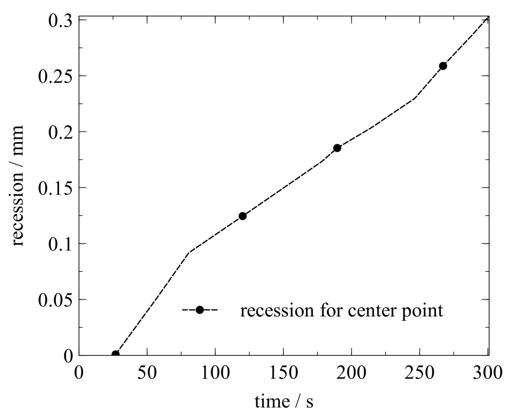

Figure 10. Quantitative recession measurement for one pixel.

recession, however, is by far lower than the photogrammetry. Laser recession with this setup gives about 0.2 mm, whereas the photogrammetry leads to 20 μm.

V. Conclusion and Outlook

In conclusion, the approach presented in this study, i.e. the application of pixelwise analysis of image pairs to analyse the 3D surface, is well applicable to plasma wind tunnel problems. Compared to classical photogrammetry technologies, significantly higher tolerance to image problems, as noise, radiation differences, is allowed and a considerably high resolution in the range of 20 μm is reached.. Compared to literature values this is a very promising result. An investigation of window effects and various camera positions has been investigated in this study, but do not influence the result significantly. A possible application of mirrors, however, reduces the accuracy by a factor of 2.

The main goal of future measurements is to analyse already mentioned issues of a high recession during beginning of ablation testing before reaching a rather constant recession rate. This observation affects a possible conclusion for a mission relevant material test with respect to safety margins.

In combination with optical emission spectroscopic analysis, the ablation process can be analysed in further detail towards better material performance prediction and thus lower possible safety margins and leightweight thermal protection systems.

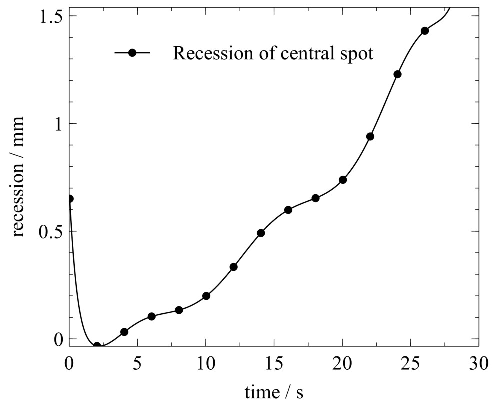

Figure 11. Quantitative laser recession measurement for central spot (diamter approx. 5 mm).

VI. Acknowledgments

The authors gratefully acknowledge the astonishingly interesting results Jens Marr, Mirko Zuber, Sebastian Hoerner, and Michael Wrasmann contributed. S. Loehle would like to thank the colleagues of the laboratory team for the support during testing. T. Reimer would like to thank Florian Hofmeister for his assistance in the basic laboratory testing.

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