A COMPARISON BETWEEN 2D PLATE CALIBRATION AND WAND CALIBRATION FOR 3D KINEMATIC SYSTEMS

Tomislav Pribanić[1], Stanislav Peharec[2] and Vladimir Medved[3]

[1]*Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia*
[2]*Polyclinic for Physical Medicine and Rehabilitation "Peharec", Pula, Croatia*
[3]*Faculty of Kinesiology, University of Zagreb, Croatia*

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Abstract:

Compared to a 2D plate camera calibration and a traditional 3D calibration cage, it is generally regarded that a wand-based camera calibration of 3D photogrammetric systems is more user-friendly. Not surprisingly, nowadays commercially available 3D kinematic systems for a human motion analysis are offering almost exclusively a wand calibration. Still a 2D calibration plate is continuously used in a number of other applications and it has potential advantages over the wand. However, there appears to be no published work comparing a 2D plate and a wand calibration, at least when it comes to the commercially available 3D kinematic systems. Therefore, in this work we compared a 2D plate calibration and wand calibration for a typical and very popular 3D kinematic system. We demonstrated that there was basically no difference in the reconstruction accuracy and additionally most qualitative issues were, as a rule, favorable to a wand calibration.

Key words: *3D kinematic system, camera calibration, wand calibration, human motion analysis*

Introduction

3D photogrammetric systems, commonly used for human motion analysis, are often referred to as 3D kinematic systems, since the very first data readily provided by such systems are so called kinematic parameters, e.g. 3D location, velocity and acceleration (Allard, Stokes, & Blanchi, 1995). Prior to 3D reconstruction a camera calibration procedure is required during which the camera function model parameters are computed, responsible for describing the process of projecting a point from a 3D space onto the camera's image sensor (Salvi, Armangue, & Batle, 2002; Wei & Ma, 1994). From a procedural point of view, a camera calibration is a series of steps that a user performs to find the camera parameters. Originally, a traditional 3D calibration cage offered all the necessary calibration data from a single image, due to the accurately known position of the redundant set of the clearly marked calibration points on the 3D cage. In photogrammetry, an accurately fabricated 3D calibration cage is still generally regarded as the most reliable way to calibrate a camera. However, nowadays, it appears that a rather user-friendly wand calibration is offered by the vast majority of 3D system manufacturers (e.g. BTS, 2008; MotionAnalysis, 2008; Vicon, 2008, Innovision, 2008), at least when it comes to commercially available 3D kinematic systems

In the case of wand calibration, the ground-truth information used to compute camera parameters is the length(s) of the calibration wand(s) (Dapena, Harman, & Miller, 1982; Hinrichs & McLean, 1995; Cerveri, Borghese, & Pedotti 1998; Mass, 1998). The angle between calibration wands can also be used as a calibration constraint (Pribanić, Sturm, & Cifrek, 2007). The wand lengths are clearly marked with markers. Thus, the user is typically required to walk through the calibration volume (a so called wand dance) and image the wand in as many locations and orientations as possible, with respect to the system cameras. The wand dance usually lasts between 60 and 120 seconds. At first that may sound like a serious drawback compared to a 3D cage where, as a rule, only a single image is required. However, in the comparison with a 3D calibration cage, the luxury of defining (changing) the calibration volume size almost exactly according to the user's needs, the relatively easy storage and the cheap fabrication of the calibration wands, and the convenient manipulation (particularly outside the laboratory) are some of the major arguments in favor of using a wand calibration.

The question naturally arises: could we combine the certain major strengths of each type of calibration mentioned previously? The answer almost intuitively leads to camera calibration using a 2D calibration plate (Sturm & Maybank, 1999). Such a calibration tool has a set of planar calibration points whose positions within a plane are accurately known. The typical calibration procedure requires positioning and imaging a 2D calibration plate on a number of locations/orientations in the space, similar to a wand dance. However, compared to a wand calibration, a single image of the 2D calibration plate provides a lot more calibration data. At the same time, compared to a 3D calibration cage, a 2D calibration plate has more attractive features in terms of manipulation, fabrication and definition of the volume size. Although 2D calibration plates are widely used in other applications and systems (e.g. calibration of 3D scanners based on structured light; Salvi, Pages & Batlle, 2004), it appears that 2D calibration plates are not used in today's commercial 3D kinematic systems. Moreover, to the best of the authors' *knowledge*, no comparative test reports of the wand and 2D plate calibration applied in 3D kinematic systems have been published.

The aim of this paper is to check the feasibility of calibrating one commercially available 3D kinematic system (otherwise designed for wand calibration) using a 2D calibration plate. More specifically, after calibrating such a system with the manufacturer-provided wand calibration tool and then again with our own routines for 2D plate calibration, we performed a series of tests to reconstruct certain ground-truth data. However, this work goes beyond merely providing the reconstruction results after calibrating with a wand or a 2D plate. We also point out in more detail some of the pros and cons of both types of calibration and we draw attention to the 3D system design required when using either type of calibration. Finally, we state as a general conclusion what type of calibration method is preferred given the particular experimental setup in this work. In general, we aim therefore to have contributed to the methodology of 3D kinematic measurement as it is being practised in the field of human movement analysis.

Method

The commercial 3D kinematic system used in this research was Smart-D, manufactured by BTS Bioengineering (BTS, 2008) and consisting of eight cameras at 200Hz. It is an optoelectronic system which actually reconstructs positions of the passive (semi)spherical retro-reflective markers, attached to the subject's points of interest. In this study, the eight cameras involved were equally distributed around a calibration volume. The system was set up in the biomechanical laboratory of the Polyclinic for Physical Medicine and Rehabilitation (Peharec) in Pula, Croatia, where it is used on a daily basis. In order to minimize the impact of the human factor and the effect of inexperience on the system use and calibration, all our experimenting with calibration tools was performed by a trained clinical technician who has more than ten years of experience in the use and calibration of various 3D kinematic systems.

The first calibration experiment assumed wand calibration according to the system manufacturer's instructions. Accordingly, the first step consisted of putting down and imaging three orthogonal wands, each one with a various number of spherical markers (20mm in diameter) and position with respect to the triad origin accurately known (Figure 1). That first calibration step aims at defining a spatial coordinate system according to the user's requests and it also provides calibration data to compute the initial values of the camera parameters. After this first step an orthogonal triad of wands was removed from the cameras' field of view and only one wand with three markers was used to do the second calibration step – a wand dance (Figure 2). During the wand dance the user is required to walk through the desired calibration volume and to image the wand in as many locations and orientations as possible with respect to the system cameras. The wand dance, according to the manufacturer's recommendations, lasted about 60 seconds. In a computational sense, the goal of the wand dance is to refine the values of the initially computed camera parameters, enforcing the accurately known wand length(s). In that calibration experiment all the image and data processing was carried out using Smart-D software.

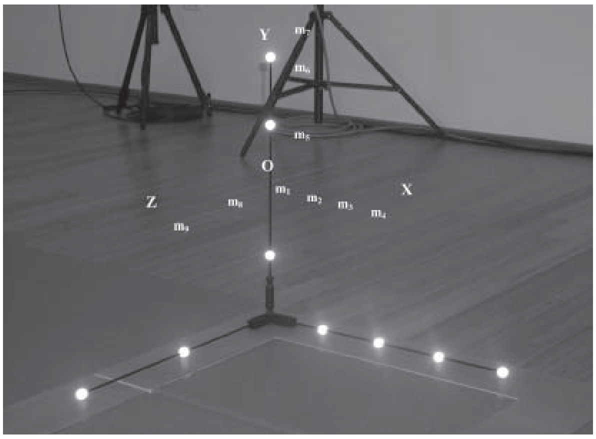

Figure 1. Wand calibration. First calibration step – an initialization of the camera parameters. Marker distances [mm] with respect to the triad origin O: X-axis m_1=150, m_2=300, m_3=450, m_4=600; Y-axis m_5=150, m_6=450, m_7=600; Z-axis m_8=300, m_9=600.

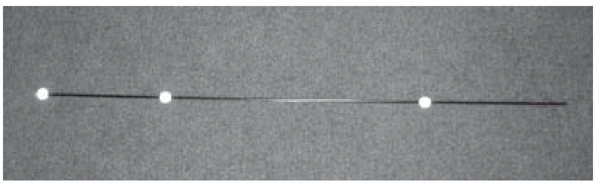

Figure 2. Wand calibration. Second calibration step – refinement of camera parameters. Single calibration wand used for 'wand dance'.

In the second calibration experiment cameras were calibrated using a custom-made 2D calibration pattern with 7×7 retro-reflective circles (made from the same material as the spherical makers mentioned previously) on a dark background (Figure 3). The circles were 20mm in diameter and they were 150mm apart. In this experiment we started right away to 'dance' with a 2D calibration plate throughout the calibration volume. There was no need to start an extra imaging session just to define a spatial coordinate system or to find the initial values of cameras parameters since all the necessary data are readily available from the dance with the 2D plate, which also lasted about 60 seconds. At the very end of it we imaged a 2D calibration plate put on the floor which allowed us to define a spatial coordinate system common to all system cameras, i.e. to establish a spatial coordinate system according to the user's requests. Smart-D detected 2D plate markers on the images throughout the frames, just like during the wand dance calibration. However, this time we exported the 2D image data of the detected 2D plate markers. We used those exported data to calibrate the system cameras using our own calibration routines written in Matlab. The calibration algorithm we implemented closely resembled the one explained in Zhang (2000). In all experiments the size of the calibration volume was around 4.0m (length) × 2.0m (width) × 2.0m (height).

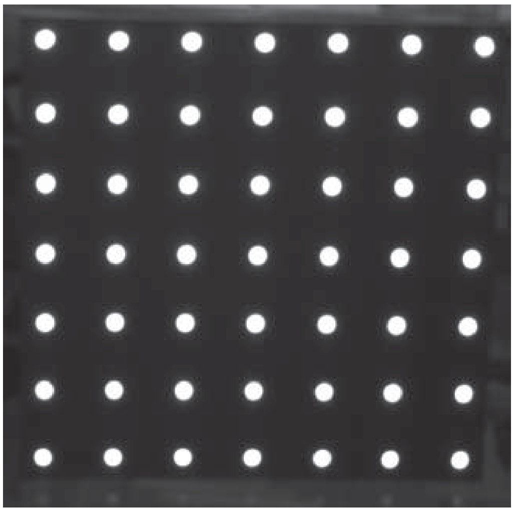

Figure 3. 2D plate calibration. 7×7 co-planar circular calibration points. The diameter of the circles is 20mm and they are 150mm apart.

To evaluate the quality of the calibration results, we used a common test where some form of the ground-truth information is typically available (Chen, Armstrong, & Raftopoulos, 1994). In fact, in our case we relied on the readily available and known distances on the wands and the 90° angle between the two perpendicular wands. More specifically, a pair of perpendicular wands is acquired after removal of the vertical wand from a calibration triad. Then, as during calibration, a dance with an orthogonal wand pair was carried out also covering the entire calibration volume and it lasted about 60 seconds as well. Next, we reconstructed wand markers throughout the frames: in one case relying on the wand dance calibration, and in the other using 2D plate calibration data. In other words, in the first case we simply let the Smart-D system provide us with its typical performance output and we only exported the ultimate 3D reconstruction results of markers for further analyses. In the latter case, we only exported 2D image data of the wand dance with orthogonal wands from Smart-D. Combining these 2D data with the previously computed calibration with a 2D plate (using our Matlab routines), we computed 3D marker positions, ready to be used for further analyses. Further 3D data analyses were the same for both calibration/reconstruction scenarios.

Results

From the perpendicular wand pair (wands defining the X and Y axes of the spatial coordinate system) we chose to represent the accuracy of the reconstruction results based on the reconstructed distances between markers m_1 and m_2 (Figure 1). The known ground distance between these two markers was 150mm. Table 1 summarizes the descriptive statistical parameters in the form of the means and standard deviations of the reconstructed distances between the mentioned markers. In addition, we considered the mean values of the absolute error between the reconstructed distances and the known ground-truth value of 150mm. Similar reports are available for other marker pairs (ground-truth distances), but are not shown in order to save space. However, to take simultaneous advantage of all available 3D data in a view we computed the angle between two perpendicular wands. Table 2 summarizes the descriptive statistical parameters in the form of means and standard deviations of the reconstructed angles between two wands. We also reveal a mean value of the absolute error between reconstructed angles and the known ground-truth value of 90°. In addition, Table 3 shows the results from the imaging and reconstruction of a static orthogonal triad of wands. This experiment served to estimate the noise of the reconstructed wand marker data, as also reported in Ehara, et al., (1997). For every marker on the wands we gave the standard deviation of the spatial coordinates obtained after a 10-second period.

Finally, the last experiment involved the imaging and reconstruction of markers stuck on the healthy patient who was walking through the calibration volume. We set 15 markers in basic accordance with the Helen-Hayes protocol (Figure 4) aimed at conducting a gait analysis as described by Vaughan,

Table 1. Mean and standard deviation values [mm] of reconstructed wand lengths throughout a large number of views during ten trials and for a particular calibration scenario. The known ground truth value is 150mm. Abserr column represents mean of absolute error [mm] between the reconstructed wand lengths and the known ground truth length

Number of views in a trial	Wand calibration			2D plate calibration		
	M	SD	Abserr	M	SD	Abserr
11009	149.826	.551	.396	149.833	.558	.398
10541	149.834	.538	.391	149.835	.587	.402
10607	149.831	.587	.399	149.831	.615	.393
10319	149.834	.600	.398	149.842	.605	.400
10420	149.839	.562	.397	149.833	.580	.397
10625	149.826	.595	.402	149.833	.534	.397
10680	149.829	.560	.400	149.825	.570	.399
11081	149.842	.591	.397	149.824	.549	.396
10617	149.838	.559	.392	149.841	.558	.396
10829	149.830	.571	.393	149.831	.579	.400

Table 2. Mean and standard deviation values [°] of reconstructed angle between two wands throughout a large number of views during ten trials and for a particular calibration scenario. A known ground-truth angle of 90°. Abserr column represents mean of absolute error [°] between the reconstructed angle of two wands and the known ground-truth angle

Number of views in a trial	Wand calibration			2D plate calibration		
	M	SD	Abserr	M	SD	Abserr
11009	90.014	.887	.417	90.022	.902	.420
10541	90.033	.745	.414	90.028	.523	.410
10607	90.024	.523	.411	90.032	.735	.414
10319	90.028	.866	.419	90.022	.515	.403
10420	90.037	.913	.417	90.040	.898	.415
10625	90.024	.521	.409	90.040	.519	.405
10680	90.027	.718	.409	90.020	.968	.417
11081	90.024	.712	.410	90.017	.948	.412
10617	90.018	.978	.418	90.034	.523	.405
10829	90.013	.960	.417	90.030	1.023	.424

Table 3. Standard deviation of the reconstructed spatial coordinates (X, Y and Z) for all the nine markers of the orthogonal wand triad (Figure 1) and for a particular calibration scenario

Marker	Wand calibration			2D plate calibration		
	X[mm]	Y[mm]	Z[mm]	X[mm]	Y[mm]	Z[mm]
m1	.054	.038	.031	.055	.038	.030
m2	.073	.046	.031	.071	.046	.031
m3	.072	.044	.039	.069	.046	.049
m4	.057	.035	.032	.056	.035	.030
m5	.057	.035	.030	.057	.034	.030
m6	.054	.025	.024	.050	.026	.025
m7	.079	.040	.033	.080	.041	.037
m8	.065	.044	.031	.060	.040	.031
m9	.061	.049	.030	.067	.048	.028

Davis and O'Connor (1999). Table 4 shows the mean distance $|m_w-m_p|$ between marker positions computed using a wand calibration (m_w) and a 2D plate calibration (m_p) (Table 4). The time interval taken to compute the mean distances was a one-stance phase.

The reconstruction accuracy is certainly one of the prevailing factors to consider, but certainly not the only one. As an additional contribution of this work we offer Table 5 where some of the most important implementation issues between 2D plate and wand calibration are compared.

Table 4. Mean value [mm] of the distance |mw-mp| where mw and mp represent marker positions reconstructed based on the wand calibration and 2D plate calibration, respectively. Mean values are computed for one-stance phase period and 15 markers were placed according to the Helen Hayes protocol

Marker	$\|m_w-m_p\|$	Marker	$\|m_w-m_p\|$
m1	.002	m9	.049
m2	.024	m10	.057
m3	.012	m11	.089
m4	.013	m12	.008
m5	.068	m13	.077
m6	.055	m14	.040
m7	.068	m15	.097
m8	.017		

Table 5. A comparison between the 2D plate and wand calibration for several key issues

Issue to be considered	Type of calibration	
	Wand calibration	2D plate calibration
An initialization of camera parameters.	An initial step required along with the wand dance procedural step.	2D plate dance sufficient for parameter initialization and refinement.
A request for a simultaneous capture of the calibration tool by two or more cameras.	Necessary in all frames of the wand dance.	Necessary only in the single frame of the 2D plate dance that will be used to define a common spatial coordinate system for all cameras.
Visibility (reflectivity) of calibration markers with regard to cameras for various spatial orientations/positions.	Spherical markers used, reflectivity characteristics should be the same in all directions.	Planar markers (circles) used, given some sharp angles and/or distance of 2D plate wrt camera insufficient amount of light will reach cameras' sensor.
Fabrication, storage and manipulation of the calibration tool, definition of the calibration volume size.	As a rule, an advantage clearly on the side of wand calibration.	
Computational cost of the calibration marker detection and tracking using infrared cameras.	Relatively easier task regarding fewer number of markers and the assumption that background does not reflect infrared light (e.g. no 'ghost markers').	Considerably more markers to detect and track. Additional processing needed to identify 'X and Y direction' of the calibration grid.
A calibration data redundancy obtained from a single (i.e. a few) image(s).	In theory, this should be an advantage in 2D plate calibration. However, the presently used popular wand calibration procedure evidently assures enough calibration data redundancy that it ultimately does not give any worse accuracy than the one based on the 2D plate calibration.	
Computational cost of the calibration marker detection and tracking using common video cameras (generally cheaper than infrared cameras such as the ones used in this work).	Potentially very demanding to detect and track marker centroids where the (parts of) image background may exhibit the same reflectance (appearance).	Still not trivial, but given the planar structure of calibration points, a rectangular calibration grid could be more easily identified on the images than a single (line) marker(s).

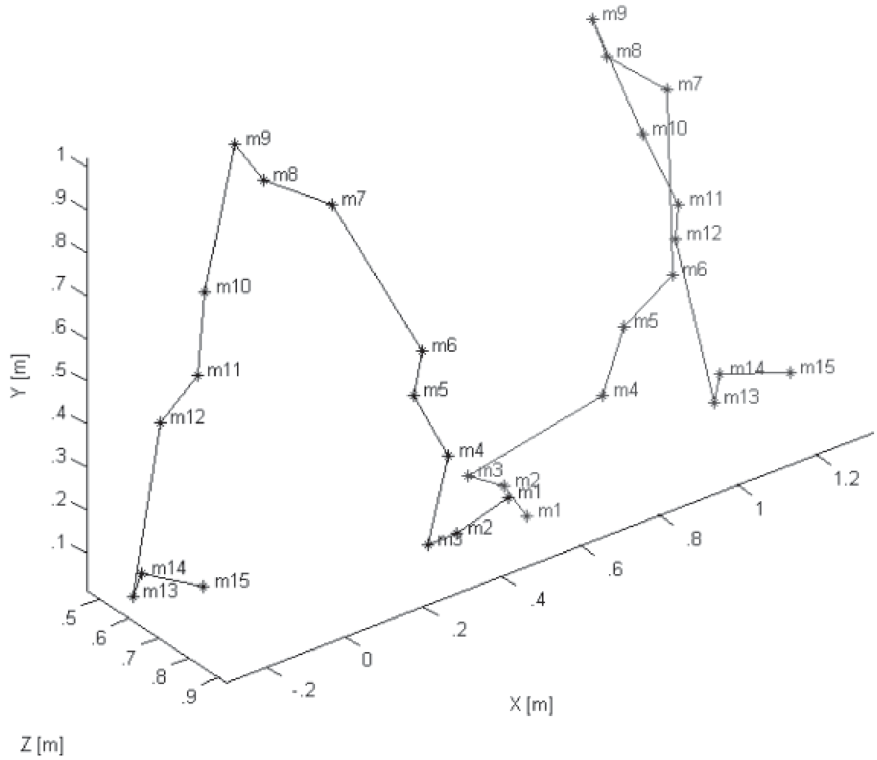

Figure 4. 3D reconstruction of markers at the beginning of the stance phase (left) and at the end of the stance phase (right). Markers m1 to m15 were set for gait analyses according to the Helen Hayes protocol as described by Vaughan, Davis and O'Connor (1999).

Discussion and conclusions

The reconstruction accuracy of 3D systems is typically evaluated through some form of known ground truth. Sometimes ground truth is the accurately known absolute position of 3D points in space. Originally, where 3D kinematic systems were calibrated using a 3D cage, such an evaluation data set was readily available (Wood & Marshall, 1986; Hatze, 1988). Alternatively, one could use additional (photogrammetric) equipment such as theodolites with vertical poles, both to calibrate volume and to come up with a data set for accuracy evaluation (Kwon, 1999). Furthermore, specially designed test objects are occasionally manufactured to evaluate the accuracy of the system (Richards, 1999). Still, readily available calibration tools, as in our case a set of wands with markers with known distances and angles between markers, are used as well. Namely, such a calibration tool is claimed by the system's manufacturer to be highly accurate (a particular quantitative measure of the obtained fabrication accuracy of the calibration tools was not available to the authors) and is typically used by the system manufacturer to report system accuracy also. Therefore, the Smart-D calibration tool is justifiably assumed in this work also to be a source for the accuracy of data evaluation. Points on the test object can be reconstructed either statically (the test object is kept still during image acquisition) or dynamically. In principle, a dynamic test is regarded as more demanding due to various sources of photogrammetric error, e.g. motion blur (De Leva, 2008). On the other hand, as already pointed out in an earlier study (Ehara, et al., 1997), a static test is considered to be an indicator of the noise of 3D data markers. Finally, it is always preferable to test a 3D system using a realistic situation for motion analysis. For the completeness of our work, therefore, we were motivated to include all three types of testing in our experiments.

Both methods ensure data accuracy based on the accurately known spatial arrangement of calibration points. Wand length(s) is(are) essentially single dimension ground-truth information whereas a 2D plate enforces a stronger (geometrical) constraint during calibration. Nevertheless, our otherwise more than reasonable initial higher expectations about 2D plate data redundancy did come into effect. The reconstruction results, including a realistic human motion reconstruction as well (Table 4), shown in the previous section, revealed a very small difference between the wand calibration and 2D plate calibration. As a rule, a deeper statistical analysis could be performed to show whether the differences were statistically significant or not. However, an equally or even more important question is whether it really matters in practice, at least in the case of human motion analysis. A fundamental question during any analysis is whether any difference is practically significant or not? In principle, apart from imperfect calibration, motion analysis is subjected to other various sources of errors (such as skin movement effects). Many of those sources would most likely mask out any potential gain, due to the improved calibration, in the accuracy improvement of such a small magnitude. In other words, supposedly, the figures shown in the tables were significantly different from the statistical point of view; we argue, from the practical point of view, that such small differences are not an issue here. Besides, our experiments follow a procedure similar to that used in many other published works, more than a dozen of which have been cited throughout this document, where basically *only* parameters from descriptive statistics are shown as the indicators during an evaluation of calibration methods and systems (e.g. Wei & Ma, 1994; Ehara, et.al., 1997; Richards, 1999; Cerveri, Borghese, & Pedotti 1998; Salvi, Armangue, & Batle, 2002). Therefore, we feel it is reasonable to state that wand calibration and 2D plate calibration are equally accurate, given the particular 3D kinematic system used and the experimental conditions. For completeness, we point out that on its company website the manufacturer claims an accuracy of less than .2mm on a volume of 3.0m × 2.0m × 2.0m. However, in our case we could not attain such accuracy which is certainly, and at least partly, due to the larger calibration volume. The size of our calibration volume was chosen in accordance with the required volume size for most of the human motion analysis tests performed in the biomechanical clinic where the Smart-D system is installed.

The very first issue in Table 5 evidently tilts in favor of the 2D plate calibration. That is also true for the second one, but usually only in cases where one would need to do a separate camera by camera calibration. However, given the typically known and fixed camera spatial arrangement, during the 60 seconds calibration time, one normally collects a sufficient amount of data by two or more cameras using a wand calibration. If calibration markers are coated with a low quality reflective material the third issue will become a serious problem for the 2D calibration. Needless to say, the 4th issue is completely on the side of the wand calibration, particularly in the case of outdoor system use. With regard to the fifth issue, fully automatic marker detection, i.e. no user intervention required during calibration data image processing, is considerably harder if using 2D plate with many markers. Next, given the current calibration algorithms involved, it appears that higher 2D calibration data redundancy does not prevail in terms of attainable reconstruction accuracy. Finally, the last issue is clearly on the side of the 2D calibration if the system uses regular common video cameras. Marker tracking throughout the frames is generally a very demanding image processing task and very likely it is far from being automatic if the system uses regular video cameras. Still, a planar structure of 2D plate calibration points can be used as an additional constraint during markers detection on the images. However, in order to simplify further the problem of marker detection, many commercial systems, such as the one used in this work, utilize infrared cameras. Interestingly, 3D kinematic systems that do use regular video cameras normally take advantage of 3D calibration cage (APAS, 2008). Namely, regardless of a heavy 2D plate calibration use in other computer vision applications, typically where single or very few cameras are involved (e.g. 3D structured light scanners; Salvi, Pagés, & Batlle, 2004), it does not appear to be a single commercial 3D kinematic system which is calibrated using the 2D plate calibration. The reason for it has never been formally stated in any published work, but we argue that the final conclusion based on the results of this work can also supply the answer to it.

We conclude that qualitative issues are mainly in favor of the wand calibration, particularly with respect to the user-friendly wand manipulation during a calibration itself. We emphasize that the end user comfort is normally one of the prevailing factors indicating in what direction one 3D system will be designed, e.g. the use of infrared cameras. Concerning an equally important issue the attainable reconstruction accuracy, according to the shown results, does not justify the use of 2D plate calibration. Therefore, without an appropriate change of the currently involved calibration algorithms, which would allow a better 2D plate calibration redundancy to come into effect, the wand calibration is still recommended.

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Correspondence to:
Tomislav Pribanić, DSc
Faculty of Electrical Engineering and Computing Sciences, University of Zagreb
3 Unska, 10000 Zagreb, Croatia
Phone: +385 1 6129 867
Fax: +385 1 6129 652
E-mail: tomislav.pribanic@fer.hr

USPOREDBA KALIBRACIJE RAVNINOM I KALIBRACIJE ŠTAPOM ZA TRODIMENZIJSKE SUSTAVE

Općenito govoreći, postupak kalibracije kamera pomoću kalibracijskog štapa je za korisnika daleko jednostavniji od uporabe kalibracijske ravnine ili trodimenzijskog (3D) kalibracijskog kaveza. Stoga ne iznenađuje da današnji komercijalni 3D kinematički sustavi za analizu ljudskoga kretanja kamere uglavnom ugađaju kalibracijskim štapom. Činjenica je da se kalibracija ravninom također rabi u brojnim ostalim aplikacijama 3D sustava, međutim, koliko je autorima poznato, čini se da ne postoje radovi koji bi usporedili kalibraciju štapom i ravninom. U ovome radu mi dajemo takav usporedni prikaz, i to u slučaju jednog komercijalnog i popularnog 3D kinematičkog sustava za analizu ljudskog pokreta. Naši rezultati pokazuju da nema razlike između te dvije metode kalibracije kada je u pitanju točnost rekonstrukcije, dok većina kvalitativnih obilježja ide u prilog kalibraciji štapom.

Ključne riječi: *3D kinematički sustav, kalibracija kamera, kalibracija štapom, analiza ljudskoga kretanja*