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OPEN ACCESS

DOI: 10.15199/48.2025.04.35

How camera temperature may affect marker visibility in motion capture systems: a case study

Wpływ temperatury na widoczność markerów w systemach przechwytywania ruchu: studium przypadku

***Abstract**. "Please warm up the system to the operating temperature before use. The temperature may affect the measurement" – this simple statement cannot be simply explained. Manufacturers of motion capture systems warn users that temperature may affect the test, but they do not describe how. This is crucial if repeatable and comparable tests are to be performed in a reliable way. This paper is the result of experience gained from thousands of tests that should have been repeatable, but not always were. The authors try to answer not only if the camera temperature affects the system, but how it affects the system. For this purpose several different scenarios have been considered, including warming up and cooling down the cameras, and gathering data related to the visibility of the markers and how their area changes. As a result, except valuable conclusions, the simple software dedicated to the OptiTrack motion capture system has been implemented and presented. Since it is often not possible to control the camera temperature at a high level, the program should be treated as an auxiliary tool.*

***Streszczenie.** „Przed użyciem proszę rozgrzać system do temperatury roboczej. Temperatura może mieć wpływ na dokładność pomiarów" – to proste sformułowanie nie może być w prosty sposób wytłumaczone. Producenci systemów przechwytywania ruchu informują użytkowników, że temperatura kamer może mieć wpływ na testy, jednak nie wyjaśniają w jaki sposób. Ta informacja jest kluczowa w kontekście wykonywania powtarzalnych i porównywalnych testów. Artykuł ten stanowi podsumowanie doświadczeń zebranych na przestrzeni tysięcy testów, których wyniki w założeniach miały być porównywalne, jednak nie zawsze takie były. Autorzy podejmują próbę odpowiedzi nie tylko na pytanie czy temperatura faktycznie ma wpływ na działanie systemu, ale w jaki sposób na niego wpływa. W tym celu rozważono kilka różnych scenariuszy, w tym przeanalizowano proces nagrzewania kamer, chłodzenia kamer i zebrano dane odnoszące się do widoczności markerów oraz zmian ich pola powierzchni. Jako efekt końcowy, oprócz wartościowych wniosków, zaproponowano proste rozwiązanie – program dedykowany dla systemu OptiTrack, który wspomaga kontrolę temperatury kamer.*

Keywords: motion capture, camera temperature, markers visibility, OptiTrack, passive markers
Słowa kluczowe: systemy przechwytywania ruchu, temperatura kamery, widoczność markerów, OptiTrack, markery pasywne

Introduction

Motion capture (MoCap) systems are an essential part of a modern robotics laboratory. They allow object(s) (e.g. markers, rigid bodies, skeletons) to be tracked effectively, providing high tracking accuracy in sub-millimetre range. This is the main reason why they are widely used in movies [1], medicine [2-3], biometric [4], sport [5] and research [6-8]. Usually the system is susceptible to some external disturbances such as electromagnetic noise and mechanical vibration, but these factors can be identified and limited [9]. This results in a stable tracking process and high object visibility. Most researchers use the MoCap as a "black box". They set up the camera in the laboratory, calibrate the system, perform the experiment(s) and analyse the collected data. All is done, more or less, according to the manufacturer's documentation and best practices. The problem can arise when the tests are performed during long sessions, divided into several days. Except environmental factors, the temperature of the cameras may be important here.

Camera's temperature affects both marker size and tracking accuracy. Cameras need to be warmed up to operational temperature and the temperature should be controlled during the session. This is often specified by the manufacturers [10]. The statement "Please warm up the system to the operating temperature before use. The temperature may affect the measurement" seems obvious. Apart from the above, there is a lack of information on how the temperature affects the tracking process and how it changes during work with the system.

The motivation for the work was the inconsistency of results obtained during long motion capture sessions, especially those divided into several days. The visibility of single markers and the rigid body was variable and more often affected small and medium sized passive markers (5.9 mm of diameter and above). The added value of this research is not only to answer the question *of whether camera temperature affects the tracking process*, but to better understand how it affects the tracking process. There is a lack of relevant research on this topic in the commonly available literature, leaving a knowledge gap to be filled.

Based on the experience of hundreds of motion capture sessions we have conducted with different camera setups, it can be clearly confirmed that camera temperature depends on several different factors. It is interesting to note that even in situations where researchers only pause a tracking for a few minutes or use the programming interfaces (API or SDK) and make some improvements in the code, the temperature can drop greatly. In addition, with some motion capture systems, even changing the frame rate may have impact on the operating temperature and the rate of temperature drops. The "drop" will be seen as fluctuating values of marker area, which in the case of the smaller markers and active size filters can results in reduced visibility of the whole object.

The document is structured as follows. Section 2 contains introduction to motion capture systems and focuses on the selected one – NaturalPoint OptiTrack. Section 3 analyses the impact of the camera temperature on the tracking quality considering different scenarios. Section 4 discusses the gathered results and proposes a simple solution to easily control the camera temperature. Section 5 provides a summary of the paper.

Motion capture characteristic

Motion capture systems are sophisticated technical solutions that allow to track objects with high accuracy. In general, the system consists of three main types of elements – cameras, ground station and markers[1]. The consideration in this paper is limited only to the systems based on the markers, mainly passive markers, which are described in detail below.

[1] Except markerless solutions.

The camera is the primary part of the system. It captures the tracking space as a 2D image, often pre-processes the image (e.g. filtering of artefacts) and provides the information related to the markers to the ground station. Very often the camera is equipped with an infrared illuminator that makes the passive markers more visible. "Visibility" is a complex term as many factors can affect it. In the case of the camera, it could be both camera settings and it's characteristics (lens type, focus, exposure, threshold, etc.).

The ground station receives information from the cameras and, based on the 2D data obtained (marker positions), builds the scene containing the markers (reconstruction process). Very often markers are visible by a camera or group of cameras, but not reconstructed into 3D space. The most common reason for this is their poor visibility (too few cameras or filtering). The system needs at least two cameras and three markers to reconstruct the scene and the rigid body [11-12]. More cameras mean more accuracy and better resistance to external disturbances.

Markers are mainly used to construct rigid bodies and skeletons and are rarely used independently. They are divided into two basic groups – active markers and passive markers. Active markers are (simplifying) LED diodes that emit light of a specific wavelength (often approx. 850 nm). The visibility of the active markers is very good and does not depend on the camera illuminators. Other advantages include compact size, lightweight and ability to increase the light output if necessary. On the other hand, the active marker requires an additional power supply and some electronic components to control the process. Passive markers (Figure 1) are spherical or flat retro-reflective materials that can be seen by the MoCap cameras. Here, it is necessary to use an external light source to make the markers visible. The visibility of markers depends mainly on their size, type and material used. Markers with a greater diameter are more visible, but cannot always be used e.g. on smaller flying robots. The circular markers are much better projected in 2D space than the flat markers, but they are much heavier and often require special stands, which adds to the weight. The material used must be retro-reflective.

Fig. 1. Comparison of different passive markers. The differences are in the material used, diameter and type (spherical, flat).

The first step before using the system is to properly place and calibrate the cameras. The placement process is an unresolved optimisation problem [13, 14]. Many approaches have been made, but there are still no universal guidelines or tools. The most important are the manufacturer's documentation, the manufacturer's guidelines and an experienced team [15]. Camera placement is the first step in achieving high quality tracking. Both position and orientation are important. The above is not strictly related to tracking systems such as Microsoft Kinect or Atracsys fusionTrack. Although the pose is relatively easy to set, the orientation depends on many factors such as lens type, focal length and field of view (horizontal and vertical). For this purpose, the real-time camera preview and any kind of simple positioning tool (Figure 2) are very useful.

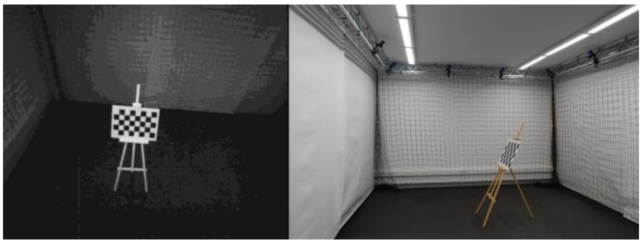

Fig. 2. Camera placement process. For the best setting of the camera orientation, the real-time camera preview and the positioning tool were used (here improper camera's orientation is visible). The brightness and contrast of the left part of the image were changed for better visibility.

The camera calibration process determines the overall accuracy of the system [9]. It should be done using dedicated tools provided by the system manufacturer. In the case of the most common (marker based) motion capture systems, two primary tools are used – a wand, which allows to determine each camera space coverage and a ruler or a triangle, which determine the ground level and the system orientation in the space. Both tools are required to the proper system calibration including determining each camera placement. The system can only be used after successful calibration. It is important, because otherwise the system cannot provide sufficient and relevant information related to each camera placement in the space, their space coverage and coordinate system of the laboratory. The information is crucial, especially when the camera placement needs to be improved or third-party application is used.

If the placement and calibration are done well, another important factor occurs – temperature. Temperature affects the visibility of the markers and increases positioning drift. The optimum temperature values are often described in the system manual, but they are difficult to maintain throughout the duration of the test, especially if the test is divided into several days. For a better understanding of how the temperature may affect the marker visibility, the correlation between camera temperature and marker area was shown in Figures 3-4. The distance between marker and camera lens was 280 cm (±1 cm).

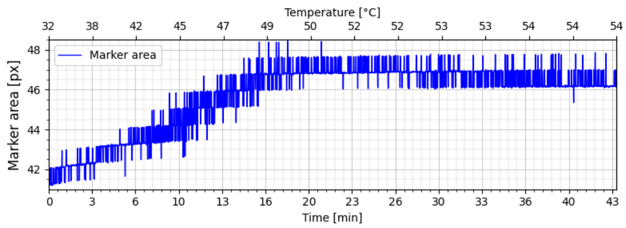

Fig. 3. Example of correlation between marker size and temperature; the diameter of the marker used was 12.7 mm.

At this point it is important to define the terms' accuracy and visibility. In this case, accuracy is an average difference between the positions measured in the group of the samples (less is better). The visibility is the ability to detect the marker expressed in area (greater is better).

Camera temperature

Before the system can be used (calibrated or used for regular tests) it must be warmed up to operating temperature. The "operating temperature" is strongly dependent on the ambient temperature, humidity, air flow and frame rate chosen. The desired camera temperature is often specified by the manufacturer. For example, in the case of the OptiTrack system, the temperature should be in the range 40ºC-50ºC or 25ºC above the ambient temperature [10]. It allows for accurate measurements, but it is not always easy to maintain the temperature. Even if the environmental conditions are fair, the capture process can be affected by temperature. If the system captures the tracking space at a constant frame rate, the change in temperature during the process will be unnoticeable. However, if the programming interface is used or the system frequently changes its state (capturing, standby, power off), the temperature variation will be noticeable and visible in the measurements.

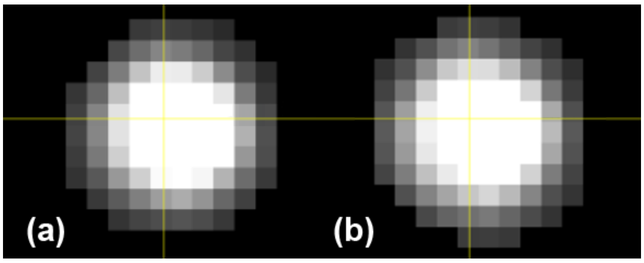

Fig. 4. Comparison of marker area depending on the camera temperature; the marker diameter was 12.7 mm; the (a) shows the marker area at temperature of 32ºC; the (b) shows the marker area at temperature of 54ºC.

1) Marker visibility

The visibility of the marker is important as it determines the overall rigid body tracking capabilities. The marker area (when the marker is projected in 2D) is variable and also depends on the distance from the camera. This means that markers with larger area (not physical diameter) can be detected from greater distance. It is important to achieve as large area as possible while ensuring stable measurements.

To better understand how the marker size depends on the temperature and how quickly the temperature of the cameras can change, two different scenarios were considered. The first one is related to the warm up process and the analysis of how the temperature changes during this process. The second refers to the cooling process.

It is important to note that additional tests, strictly related to the markers themselves were also performed. The markers were heated up to about 60ºC and cooled down to about –10ºC. Their visibility was checked and compared with the ambient temperature markers. No changes in the area of the markers were observed between the groups. The only observed phenomenon was a (temporary) change in the surface area of the cooled marker, which however, was more closely related to water condensation (on its surface).

2) Warming up

The warm up tests cover three scenarios: when the cameras are only powered on (no communication), when the cameras are used for capturing and when different numbers of markers are visible and tracked.

The first scenario relates to the situation where the cameras are powered up and connected to the infrastructure (the system), but capturing is not active. The change of temperature in the time was shown in Figure 5.

As the temperature rise was very, very slow and did not reach operating temperature, only the first 60 minutes of the test with step of 10 minutes were shown. For this reason, the correlation diagram between temperature and marker size was not attached here. In this case the ambient temperature was (25±0.5)ºC. According to the manufacturer's guidelines, the operating temperature should be about 50ºC or higher. This clearly shows that simply turning the cameras on is not a sufficient warm up procedure.

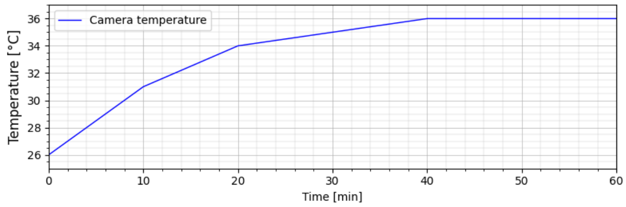

Fig. 5. The change of temperature in the time when the system is only powered on and capturing is not active. Due to the very slow temperature rise, the number of measurements was limited for readability.

The second test was performed when the system was used to track an object. In this case, one of the dedicated programming interfaces (Camera SDK) was used, as it allowed all sufficient data to be gathered. The camera temperature reached operating temperature after about 25 minutes and was fully stabilised after about 64 minutes (Figure 6).

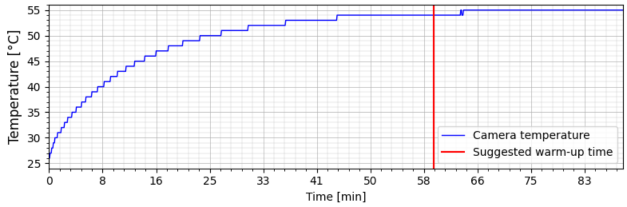

Fig. 6. The rate of the temperature rise when tracking space is captured.

As shown in Figure 7, the marker area has changed during the session. Below the operating temperature it was noisy and fluctuated. In the case of the smaller markers, too low temperature could limit their visibility, as the minimum size filter in post-processing would just cut them off. What is more, the fluctuation in the marker area can lead to a change in centre of the detected marker, which will affect the whole rigid body.

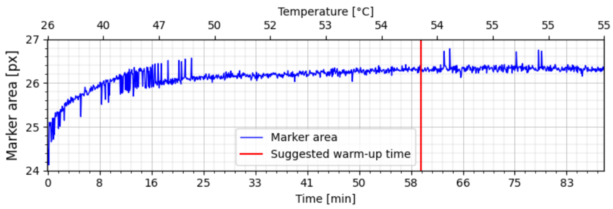

Fig. 7. The changes in the marker area during the test. The temperature of the camera affects the area and could limit the visibility of the marker if it is too low. The diameter of the marker used was 12.7 mm.

An additional test was related to warm up process, when different numbers of markers were visible by the camera. As the number of detected markers has an impact on the amount of data transmitted between the camera and the ground station (Table 1), there was a possibility that it might also affect the warm up time (more markers = faster warm up). The test covers zero, one, two, three and seven visible markers at the same time by single camera. The difference between zero and seven markers was at the level of 1ºC-2ºC during the test time, which can be treated as measurement error or environmental factors rather than a real effect of the number of visible markers. The warming up diagram was similar to those in the second scenario (Figure 6).

Table 1. Amount of data transmitted by a single camera depending on the frame rate and number of visible markers in the case of the OptiTrack system (Prime^x 13W camera). Values are expressed in KB/s.

Frame rate [FPS]	Amount of transmitted data [KB/s]				
	Number of markers				
	0	1	2	3	7
50	2.0	3.0	4.1	5.2	9.5
100	3.9	6.1	8.2	10.4	19.1
150	5.9	9.1	12.4	15.6	28.6
200	7.8	12.2	16.5	20.8	38.2
250	9.4	14.6	19.8	25.0	45.8

3) Cooling down

The cool down tests considered two cases – when the cameras were powered on, but there was no communication and when they were in standby mode (idle). Both situations are very common, when researchers are analysing gathered data or making improvements in code using motion capture programming interfaces.

The results of the first test – powered on without communication – was shown in Figure 8. The temperature drop is noticeable, and after 6 minutes the system should be warmed up again, before use. After 10 minutes of idle the fluctuation in the marker area may occur and introduce additional measurement error.

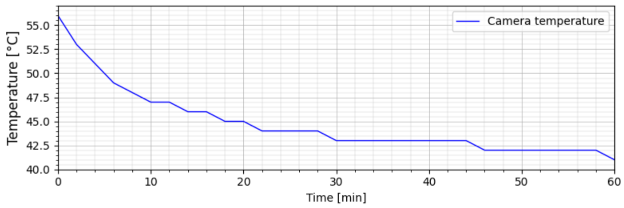

Fig. 8. The change of temperature in the time when the system is powered on and capturing is not active.

The second case concerned the situation where the software provided by the manufacturer is active, but live mode is disabled (e.g. edit mode). The data gathered showed that (in the Motive software) there is some sort of built-in subsystem that keeps the temperature very close to the operational level. It provides the ability to switch to capture mode and perform tests without checking the temperature and "reheating" the cameras. The mentioned subsystem is not available in the programming interfaces.

Rigid body positioning

As shown in Figure 7, the temperature of the cameras affects the marker area. By changing the area, especially if there are fluctuations in the measurements, the centre of the marker may be changed. For the purpose of the test, a rigid body was constructed based on four markers. The rigid body was placed on the floor and did not move during the session. The laboratory, single camera and rigid body coordinate systems are shown in Figure 9.

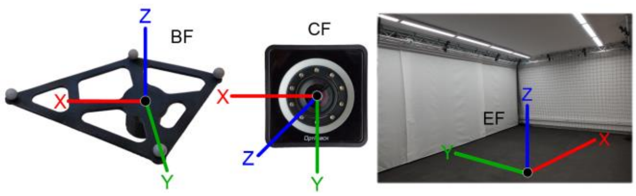

Fig. 9. Comparison of coordinate systems. The *EF* means *Earth Frame* and it is related to global OptiTrack coordinate system. The *BF* means *Body Frame* and it is related to tracked object (tool). The *CF* means *Camera Frame* and it is related to single camera.

Minor measurement drift was expected as it is part of the vision based tracking systems. The total test duration was seven hours. As the drift after the warm up was very small, only the results of the first 180 minutes have been presented (Figures 10-12).

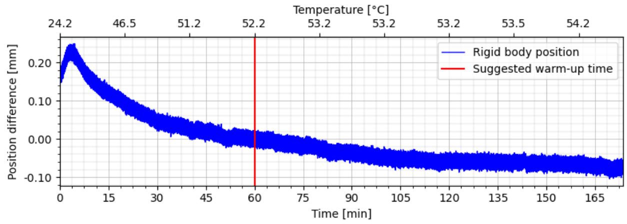

Fig. 10. Measurement drift in the x axis; the data has been normalised and shows the difference in measurement compared to the position when the system was fully warmed up (60 minutes).

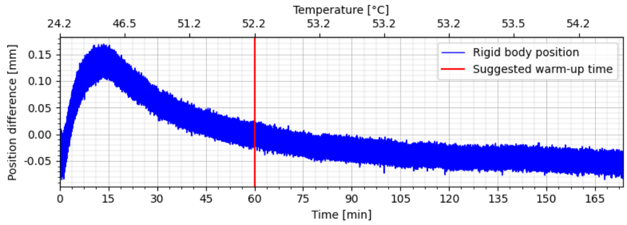

Fig. 11. Measurement drift in the y axis; the data has been normalised and shows the difference in measurement compared to the position when the system was fully warmed up (60 minutes).

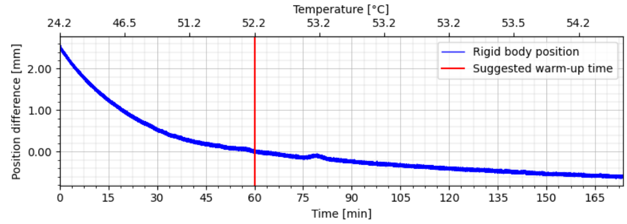

Fig. 12. Measurement drift in the z axis; the data has been normalised and shows the difference in measurement compared to the position when the system was fully warmed up (60 minutes).

The position of rigid body in x and y axes has changed noticeably in the first stage (before reaching the operating temperature) and after that the measurement error has been gradually increasing. The measured position difference is above 0.1 mm in the case of the x axis with total changes over 0.2 mm and below 0.05 mm in the case of the y axis with total changes over 0.2 mm. The situation is different for z axis (Figure 12). Here the positioning error is high, reaching over 2.0 mm. Once the temperature has been stabilised the measurement drift slowed down considerably.

It is important to note that the measurement drift will have less effect on the positioning data if the object performs the movement. This case has not been considered here, as there should be another ground truth system with a higher accuracy than the system tested.

Discussion

The tests performed clearly show that the temperature of the cameras is a crucial factor and must be taken into account if comparable and repeatable research is to be carried out. In addition to the well-known manufacturer's guidelines on temperature, we can now answer not only whether temperature has an effect, but also how it affects the results.

Our first consideration is the change in temperature during the session. If the system is just powered on and there will be no communication (capturing), the system will warm up only a few Celsius degrees above the ambient temperature (Figure 5). This is much lower than manufacturer suggests[2]. When capturing is on, the temperature rises much faster, reaching operating temperature and above (Fig.6). It is important to note, that some software has built-in solution that keeps the temperature of the cameras at a level close to the desired one. It is not always implemented and possible to use. For example, if the programming interface is used, and there is a pause between tests (e.g. to analyse gathered data), the temperature may drop to an undesirable level. The drop will be seen as a fluctuation in the marker area, making it less visible. The speed of the temperature drop depends on the ambient temperature. In the test case, when the temperature in the laboratory was (25±0.5)ºC, 6 minutes of the idle time, the system should be warmed up again (Figure 8).

Temperature is also closely related to marker visibility and rigid body positioning. In the first stage, as the temperature increases, the area of the markers also increases (Figure 7). The marker area is not stable and the measurement is very noisy. Based on the tests conducted, the area changes even by about 8–11%, what was presented in Table 2. This can be very important, when smaller markers are used and the size filter is active. The second stage is stabilisation. The marker area changes unnoticeably and the fluctuation in area size is greatly reduced. As the visibility of the marker has an effect on the rigid body reconstruction process and the positioning of the rigid body (if the area changes, the centre of the marker may also move to a different place), it is important to analyse how the temperature can affect this. Vision-based tracking systems often have some kind of measurement drift. This is often minor and negligible. If the temperature of the cameras is not valid, the readings can be noisy, especially in the first stage of the measurement (Figures 10-12). What is worse, there is a possibility that the differences are counted in millimetres (Figure 12), which could introduce high error into the data gathered[3].

Table 2. Differences in marker area depending on marker size.

Marker type	Marker area [px]			
	Temperature [ºC]		Area difference	
	32ºC	54ºC	Δ_{px}	$\Delta_{\%}$
OptiTrack ø7.9	8.623	9.280	0.657	7.62
OptiTrack ø9.5	21.961	23.839	1.878	8.55
OptiTrack ø12.7	41.702	46.372	4.670	11.20

Solution dedicated for OptiTrack

The problem of controlling the temperature changes is not simple and cannot be solved easily if manufacturers do not offer this as a feature in their software. Despite the above, it is a possible to prepare the stand-alone application using a dedicated programming interface and external hardware that meets the needs.

In the case of the OptiTrack system, programming interfaces allow the temperature of each camera in the system to be obtained. In combination with external thermometer and official documentation [10] the operating temperature can be calculated and checked. For ease of use, the current temperature of each camera can be visualised on its LED rings (Figure 13). This is particularly useful as it is very difficult to identify cameras by their serial number only.

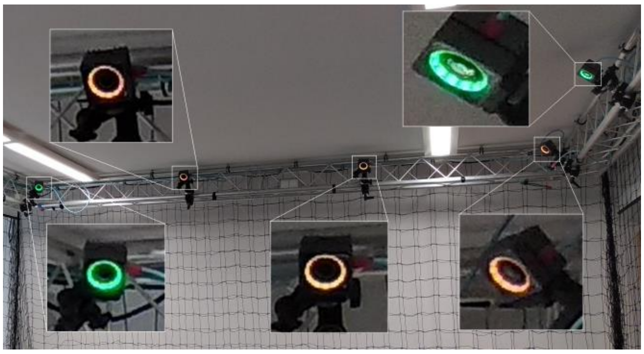

Fig. 13. Motion capture system with visible LED rings of Prime^x 13W cameras; the orange colour indicates that a camera has not yet reached operating temperature.

The general idea was to measure the ambient temperature in the laboratory and compare it in real time with the temperature of each camera in the system. In our case, the OptiTrack system and an external thermometer were used. The application was written in `C/C++` programming language using a low-level camera programming interface – Camera SDK. The thermometer was a commercially available `DS18B20` unit that communicates via a 1-wire interface. For ease of use, the 1-wire to USB converted was used (`FT232RL` and `DS2480B` modules). This makes it possible to use the thermometer with any computer equipped with a USB port (Figure 14).

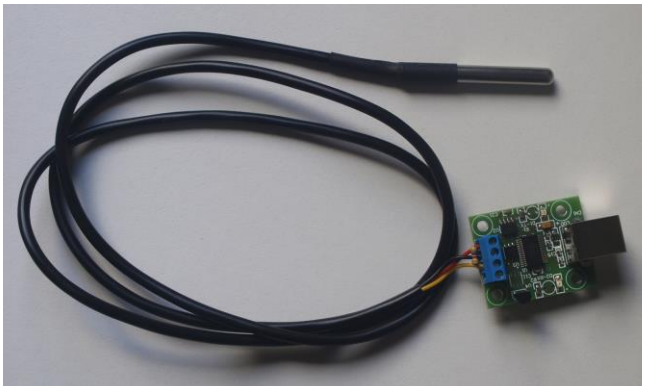

Fig. 14. DS18B20 thermometer and 1-wire to USB converter module; the data from the thermometer can be read directly in an application written in *C/C++* programming language.

The solution is very useful during long motion capture sessions, especially divided into several days, to make sure the system temperature is the same. It is also desired when programming interface is used and there is a risk, that cameras may cool down in meantime between tests, which in consequence could affect markers visibility or measurement.

Code with required libraries was provided as external resource[4]. If the user is going to use the same modules as mentioned above, it is only necessary to modify two constants – `TEMPERATURE_OFFSET`, which refers to the difference between the ambient temperature and the camera temperature, and `COM_PORT`, which indicates the port of the external thermometer, as it may be different for each device. It is also possible to use any other external thermometer. The functions `init_module()`, `get_external_temperature()` and `release_module()` will have to be rewritten.

[2] In the case of OptiTrack, the difference between the ambient temperature and the camera temperature should be approximately 25ºC.

[3] The manufacturer's declared accuracy is 0.3 mm when using a 14 mm marker and camera settings of 800 exposure, 6 of gain, and the lowest f-stop.

[4] https://chmura.put.poznan.pl/s/EhjQ9eShbibdTOT

Conclusion

This paper presents and analyses the effect of camera temperature on marker visibility, area and positioning accuracy. Several different scenarios related to the warm up and cool down processes have been considered. The conclusion is simple – it is not possible to perform reliable and comparable tests without properly warming up the system and keeping the operating temperature. In addition, constructing the rigid body, when the system is not at operating temperature can lead to problems with accurate positioning of the rigid body. The paper will be useful for those, who work with motion capture system and have met the problems related to inconsistency in the gathered data.

As the tests conducted showed (Table 2), the temperature of the cameras can affect the visibility of the marker by changing its area even by about 8–11% and introducing an error in the positioning accuracy. In some cases, the positioning error can even reach millimetres. To avoid the temperature drops and fluctuations during the pause between tests, any tool that captures the tracking area in the background when proper data is not being gathered can be used. For this purpose the proposed application will be a good solution.

Future work will be related to the retro reflective materials, their visibility in the motion capture system and how they allow the weight of passive markers to be reduced in the case of robots with limited payload capacity. As the number of tests to be performed is very high and takes many days, the conclusion described in the paper will be very valuable.

This research was financially supported as a statutory work of Poznan University of Technology (No. 0214/SBAD/0250).

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