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A Digitalized Camera Selection Tool for Photogrammetry Scanners

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Abstract. Choosing a suitable camera for photogrammetric-based scanners requires a comprehensive evaluation and an in-depth understanding of various factors, such as image quality, feature identification, field of view, working distance, etc. This study aimed to develop a digitalized tool that encodes available knowledge and best practices related to camera optics and imaging theory to facilitate metrologists' informed decision-making in camera selection for 3D photogrammetric scanners. MATLAB® was used to develop and implement the digitalized support tool and the related algorithms. Additionally, a user interface was created to facilitate the user to reach a recommended camera specification for a given application scenario. A specific scanning requirement was used as a case study to evaluate the developed tool, and the inclusiveness of the resulting data was tested using two different commercial industrial camera vendors. The results proved that the digitalized tool successfully closed the gap of knowledge metrologists may be challenged due to the different fields of expertise.

1. Introduction

Dimensional Metrology is the art of measuring length, angles and other related geometric parameters of manufactured products. Proper measurement results are a key factor in manufacturing to ensure the achievement of encoded design intent or for enhancing, redesigning or even remanufacturing objectives. Measurement techniques have evolved from using human body parts as a reference to reaching well-defined length standard units to ensure consistency. The earliest measuring tools can be traced back to the ancient Pharaonic era, where the royal Egyptian cubit was introduced. This was followed by the development of various measurement instruments, such as rulers, vernier calipers, protractors, and micrometers, which were widely used for many years. Eventually, the advent of coordinate metrology revolutionized measurement by enabling the digital simulation of physical product geometries through coordinate measuring systems (CMS).

Figure 1 shows how manufacturing metrology is transformed into a digital age via the development of CMS, including contact-based and noncontact technologies. Nowadays, numerous optical techniques come to market of the manufacturing metrology with many different technologies such as phase shifting, structure from motion, Laser scanning and others [1]. Non-contact coordinate metrology methods share common advantages; however, they suffer from some shortcomings. A brief comparison between contact and noncontact measurement methods is illustrated in Table 1. Today, non-contact coordinate systems become the backbone for Integrated and digital manufacturing environments. Among the key benefits of noncontact measurement systems are their ability to measure a wide range of object sizes and features [2–5] and their suitability for fragile material digitisation. On the other hand, its accuracy is

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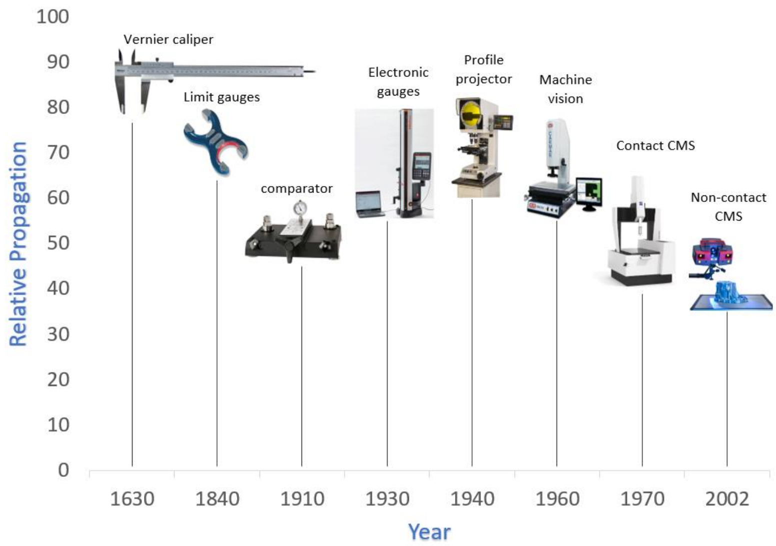


Figure 1. Historical technological milestones in metrology

Table 1. Comparison between contact and non-contact coordinate measuring

	Contact	Non-contact
Measuring speed	Lower	Higher
Suit fragile material inspection	Lower	Higher
accuracy	Higher	Lower
Cost	Higher	Lower
Measuring range	Smaller	Higher

questionable compared to contact-based technologies [6]. This paper targets these accuracy concerns by providing a digital tool that assists the scanners' manufacturers in the proper selection of the critical sensing elements of their scanners or the metrologists during the comparison of different scanners for specific scanning requirements.

2. Methodology

3D photogrammetric scanning systems include many subsystems that require various decisions during the design phase of the scanner. These subsystems are the scanner's mechanical system, electronics, control system and cameras, as sensing elements. The proper selection in each stage is crucial for the final scanner's overall functionality, accuracy, and versatility. This work focused only on selecting the proper camera, which is the main sensing element of the photogrammetric scanners and similarly for any machine vision system, as illustrated in Figure 2. The selection of the camera is a complicated problem. It includes the determination of many different parameters of the camera, such as sensor size, resolution, sensor type, depth of field, etc., while considering other objectives, such as the required size limits of the inspected products, the overall scanner dimensions and cost.

2.1 Camera model

Camera models describe the projection of the three-dimensional physical space onto the 2D image plane. This work uses the thin lens camera model as its basis for the camera selection tool, which represents the image formation process more realistically compared to the simplified Pinhole camera model. Figure 3 illustrates the difference between the basic theory of the two mathematical camera models. In the thin lens camera model, the pinhole is replaced with a lens; thus, all rays of light that are emitted by some point P are refracted by the lens such that they converge to a single point P'. The figure also shows the difference between focal length definitions in different camera models.

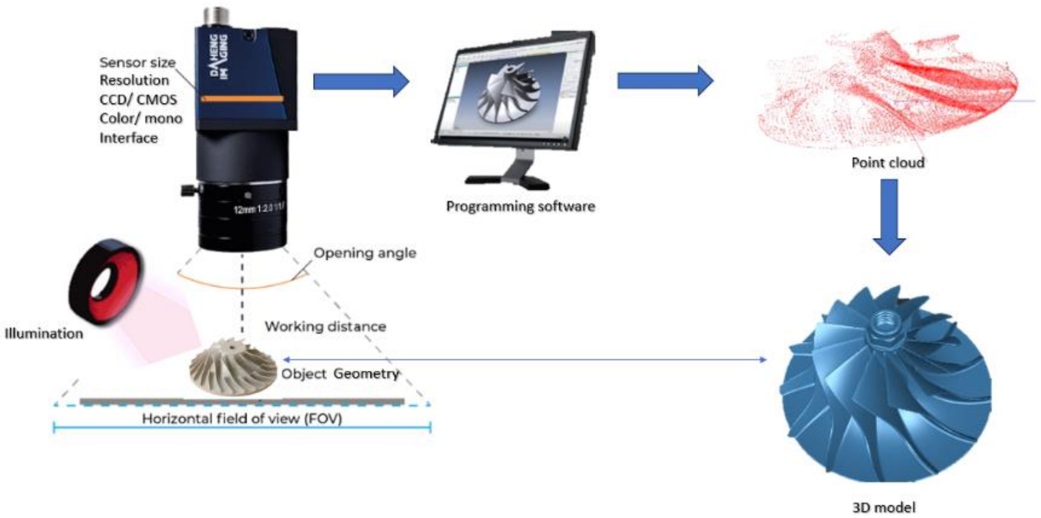
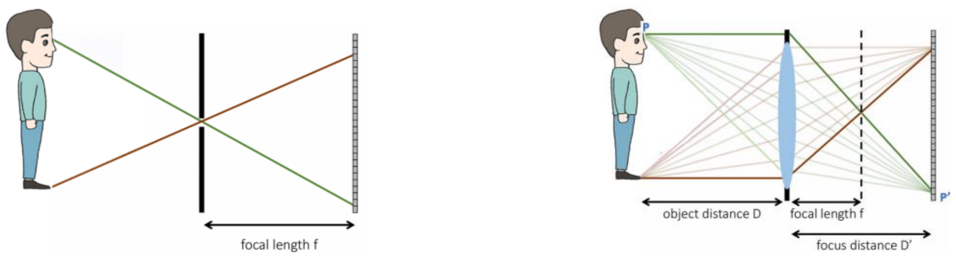


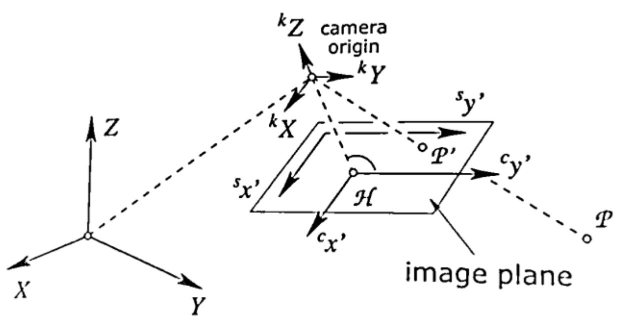
Figure 2. Main elements of a machine vision photogrammetric system



(a) (b)

Figure 3. Camera models: (a) Pinhole Camera Model, and (b) Thin-lens Camera Model, modified from [22]

The image formation processes involving the projection of a 3D scene onto a 2D image plane and the geometric construction of this process and the related coordinate systems are shown in Figure 4. As shown in Figure 4, both the camera coordinate system (CCS) and its image coordinate system (ICS) are positioned relative to the world coordinate system (WCS). The position and the orientation of the CCS relative to the WCS are named as the extrinsic parameters of the camera, mathematically encoded as ${}^{k}H_{o}$ transformation in equation (1) and expanded in equation (2).



World/Object coordinate system (WCS), S_o: [X, Y, Z]
Camera coordinate system (CCS), S_k: [X^k, Y^k, Z^k]
Image coordinate system (ICS), S_c: [X^c, Y^c].
Sensor coordinates system (SCS), S_s: [X^s, Y^s]

Figure 4. Main Coordinate Systems used in 3D reconstruction processes [7]

$$\begin{bmatrix} x^s \\ y^s \\ 1 \end{bmatrix} = {}^sH_c \, {}^cH_k \, {}^kH_o \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{1}$$

$${}^kH_o = \begin{bmatrix} R & -R\,X_o \\ 0^T & 1 \end{bmatrix} \tag{2}$$

Where:

- ${}^sH_c$ is the transformation from image plane to sensor.
- ${}^cH_k$ is the transformation from camera to image plane.
- ${}^kH_o$ is the transformation from object to camera, representing the extrinsic camera parameters.
- X, Y and Z represent the position of point P in the S_o coordinate system, as shown in Figure 4.
- x_s, y_s are coordinates of the imaged point P in the S_s coordinate system, as shown in Figure 4.
- R is a 3x3 rotation matrix of the camera relative to the S_0, and X_0 is the translation vector of the S_k coordinate system relative to the S_0 coordinate system.

The sensor coordinate system (SCS) is simply a transformed image coordinate system to match the sensor position and size in the image plane. A point P positioned relative to the CCS is imaged via the camera and projected onto the SCS. The overall transformation between the point positioned in the 3D world coordinate system and its corresponding projected image in the 2D sensor coordinate system, assuming a perfect lens without nonlinear errors, is represented in homogeneous coordinate form [7], as shown in equation (1).

Figure 5 presents the overall mathematical transformations between different coordinate systems shown in Figure 4 to illustrate the relationship between each coordinate system and the other systems. The final transformation to S_a is the SCS after correcting nonlinear errors in the camera lens, if exist. In Figure 5, it should be noted that the red arrow represents an irreversible transformation as the depth information is lost during the projection from the camera coordinate system into the 2D image coordinate system. On the other hand, all green arrows represent reversible transformations between other coordinate systems and these transformations are used in the 3D reconstruction process.

The camera has five intrinsic parameters based on this transformation chain. The first intrinsic parameter is the camera constant (c), which represents the distance from the principal point of CCS to the ICS, as shown in Figure 6. The following parameters, (x_h) and (y_h), represent the linear transformation in both X and Y directions of the ICS to the SCS. This means the distance of point H in Figure 4 from the origin of the SCS, S_s. The third parameter is the sensor scale difference (m) between both x and y directions, and finally, the shear compensation parameter (s) of the sensor, as shown in Figure 7. These intrinsic

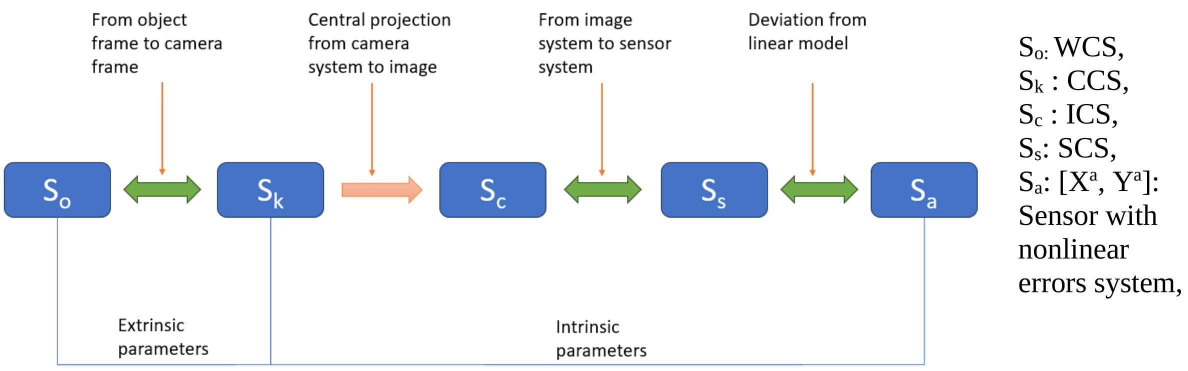


Figure 5. The overall image mapping from 3D real world to 2D image sensor

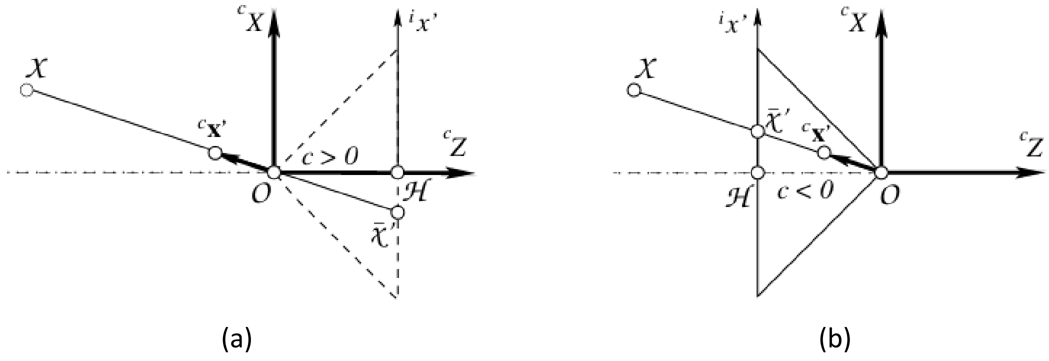


Figure 6. (a) Camera Constant, and (b) the inversion of the image plane in front of the principle point to obtain a noninverted projected image [7]

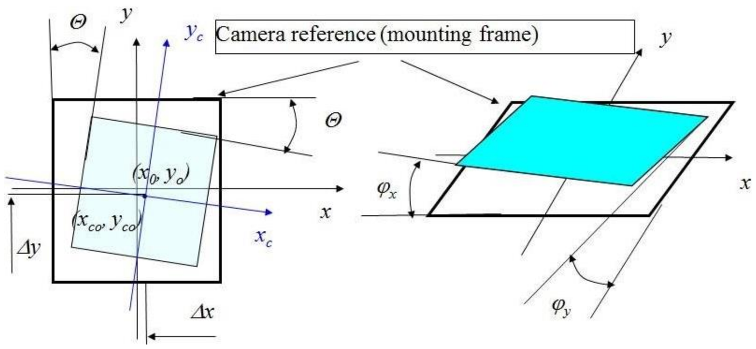


Figure 7. shear compensation for a camera sensor [23]

parameters of the camera are mathematically encoded in equation (1) as ${}^{s}H_c$ and ${}^{c}H_k$ and are expanded in equation (3) and equation (4).

$$ {}^{c}H_k = \begin{bmatrix} c & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3) $$

$$ {}^{s}H_c = \begin{bmatrix} 1 & S & x_H \\ 0 & 1+m & y_H \\ 0 & 0 & 1 \end{bmatrix} \quad (4) $$

The expanded form of equation (1) can be then represented mathematically without considering nonlinear errors as presented in equation (5).

$$ \begin{bmatrix} x^s \\ y^s \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & S & x_H \\ 0 & 1+m & y_H \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c & 0 & 0 & 0 \\ 0 & c & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} R & -R\,X_o \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (5) $$

The multiplication of ${}^{s}H_c$ and ${}^{c}H_k$ is called the camera calibration matrix K, as illustrated in equations (6) and (7).

$$ \begin{bmatrix} x^s \\ y^s \\ 1 \end{bmatrix} = \begin{bmatrix} c & cS & x_H \\ 0 & c(1+m) & y_H \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R & -R\,X_o \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (6) $$

$$\begin{bmatrix} x^s \\ y^s \\ 1 \end{bmatrix} = K \begin{bmatrix} R & -R\,X_o \\ 0^T & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{7}$$

Camera calibration activity is used to estimate the camera's extrinsic and/or intrinsic parameters as defined in equation (5). Different methods can be used to calibrate the camera, such as direct linear transform (DLT) [7], Zhang's method [8] and others [3,9–11]. DLT methods estimate the camera parameters based on the relation between known control points in the world coordinate system and their corresponding imaged points on the camera sensor; a checkerboard pattern such as shown in Figure 8 can be used for this purpose.

Other nonlinear parameters are included in the real imaging systems due to imperfections such as lens distortions, i.e. barrel distortion, fish eye distortion or pincushion, and the degree of planarity of the sensor. This nonlinearity causes a modification to the camera calibration matrix K into the mathematical form presented in equation (8)

$$K = \begin{bmatrix} c & cS & x_H + \Delta x \\ 0 & c(1+m) & y_H + \Delta y \\ 0 & 0 & 1 \end{bmatrix} \tag{8}$$

2.2 Basic principles of camera selection methodology

Various parameters and/or options need to be decided when selecting a camera that fits well-defined photogrammetric-based scanning requirements. This section introduces the implemented methodology in the proposed digitalized camera selection tool presented in this work. Imaging parameters were categorized as being calculated, selected or recommended, as shown in Table 2. Five parameters are required to be evaluated using the previously discussed imaging principles and the normally specified scanning requirements.

Focal length theoretically determines the required lens for the required sensing camera. Typical increments of focal lengths are 1.8, 2.8, 4, 6, 8, 12, 16, 25, 35, 50 and 75 mm. equation (9) states that to calculate the focal length, the sensor size, working distance and scanned object size need to be decided.

$$f = \frac{g}{\frac{G}{B} + 1} \tag{9}$$

Where:

- f is the camera focal length (mm).
- g is the scanning working distance (mm).
- G is the maximum length of the scanned object (mm) and is related to the camera's field of view.
- B is the sensor height (mm) and represents the sensor size (sensor designs have a fixed aspect ratio).

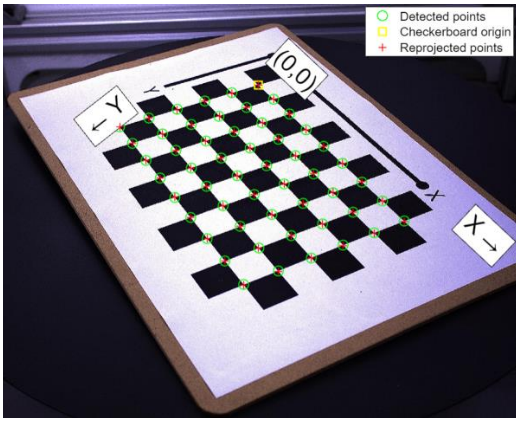


Figure 8. Checker board used for camera calibration

Table 2. Categorization of Camera Parameters

Calculated parameters	Recommended Parameters (based on a technical survey)	Selected parameters (based on working conditions)
• Sensor size • Depth of field • Pixel density (dependent) • Field of view (dependent)	• Focal length • Sensor type (CCD/CMOS) • Lenses mount. • Circle of confusion diameter • Sensor size	• Shutter speed • ISO number • Aperture size • Working temperature effect

In equation (9), both the working distance (g) and the maximum length of the scanned object (G) are targeted specifications of the 3D scanner under development. The remaining unknowns are sensor size and focal length; one of them should be selected to be able to evaluate the other one. Based on the authors' survey of some commercially available 3D close-range photogrammetry-based scanners and some scanners used in the academic literature[12–14]; it was observed that the commonly used focal length is 12 mm [15–18]. In the same context, it was also observed that cameras with a resolution from 3 to 12 MP are used extensively in mid-range photogrammetric scanners where 5 MP is the most frequently used resolution.

In addition, sensor sizes of 2/3", 1'', 1/3" and 1/1.8'' were also common. Based on the recommended focal lens, sensor size is then calculated via equation (9). Sensor size primarily affects the amount of light captured by the camera sensor. On the other hand, camera resolution depends on the pixel size and pixel density per squared area. Larger pixels have the potential to capture more light, which can result in improved image quality, especially in low-light conditions. However, when it comes to image resolution, a higher density of pixels enhances captured details in an image; this is crucial for photogrammetry and accurate 3D reconstructions [7,19,20]. A trade-off exists when selecting a camera for scanning applications between sensor size and its corresponding sensor resolution. equation (10) mathematically presents the relationship between sensor size and image resolution, in which the pixel density (D) can be calculated as:

$$D = \text{Resolution} / (\text{Sensor Width x Sensor Height}) \quad (10)$$

Moreover, the depth of field (DOF) is directly related to the scanned object size. It signifies the range within which an object is at an acceptable level of focus and sharpness, as shown in Figure 9. Depth of field is calculated as presented in equation (11).

$$Dof = \frac{2U^2 Nc}{f^2} \quad (11)$$

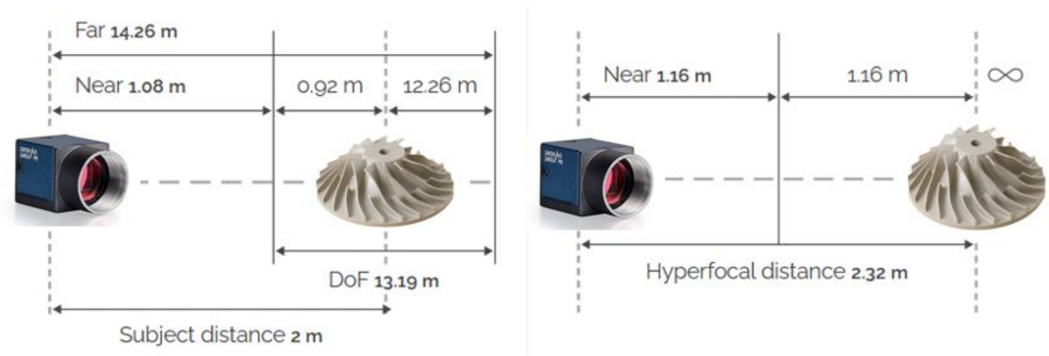


Figure 9. Example explaining the DOF concept

Where:
- c is the circle of confusion (mm).
- N is the f-number.
- U is the working distance (mm).
- f is Focal length (mm).

Circle of confusion (c) is a key concept as the imaged object is a 3D body instead of being a planner object; thus, some of the projected rays on the image sensor do not perfectly intersect at the focal distance. The circle of confusion is the size of the minimum circular shape that surrounds these collected rays and determines the degree of clearness or blurriness of the imaged object, as shown in Figure 10. The same defined parameters in the last equation are also used in equation (12) to determine the hyperfocal distance (H) that is used in determining the near and far limits of depth of field from the camera sensor as shown in equations (13) and (14). Within this range, the scanned part is in focus, and its scanned images can be analyzed via photogrammetric algorithms, as illustrated in Figure 9.

$$H = f + \frac{f^2}{N * c} \quad (12)$$

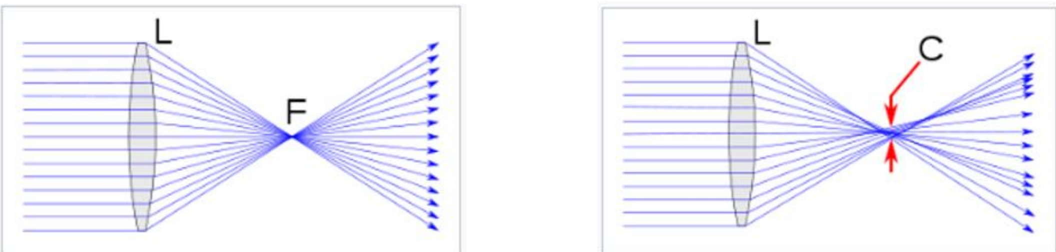
$$DoF_{\text{far limit}} = \frac{H \times U}{H - (U - f)} \quad (13)$$

$$DoF_{\text{near limit}} = \frac{H \times U}{H + (U - f)} \quad (14)$$

Other parameters such as ISO setting, shutter speed and connectivity type are important to be determined explicitly during the camera selection phase; however, they are not an integral part of the imaging process itself. For instance, the lens mount to a camera system can be either threaded or a bayonet-type mount. The lens mount and camera should be compatible with the used mount. In addition, sensor types such as the coupled-charge device (CCD) and complementary metal oxide semiconductor (CMOS) are popular in the camera sensor market. It was observed that based on size, functionality, performance and cost parameters, the CMOS is preferable in most machine vision applications [12,21].
Finally, the type of connectivity between the camera and the photogrammetry processing system is a final matter that needs to be considered during the scanner design based on the user preferences and application requirements. The selected connection technology directly affects the transmission speed, range and overall cost.

3. Implementation

It should be emphasized that a metrologist, in most cases, is unaware of the concepts introduced in the last section. This knowledge gap is considered a barrier when a metrologist is required to design or even select a scanning resource for prespecified metrological requirements. In this context, this section considers the implementation of the proposed digitalized tool that captures the knowledge to assist metrologists in determining the proper camera for their intended application. MATLAB was used to encode this knowledge to create a tool that starts from what the metrologist requires in a given scanning



(a) (b)

Figure 10. Circle of confusion (C): (a) Perfect lens and (b) Imperfect lens [24]

scenario. These technical needs are used to guide the metrologist towards the final recommended camera specifications that properly suit these requirements. The developed tools process the input requirements as described in the flowchart shown in Figure 11. In addition, a graphical user interface (GUI) was developed for the encoded assisting tool, as shown in Figure 12.

The implementation process starts by requiring the user to select a focal length for the target lens, while the system can also recommend values to assist the user. The system provides the option to the user to start by specifying the required sensor size instead of the focal lens however, this is not the commonly assumed case. The user is then requested to input his geometrical scanning needs that represent the

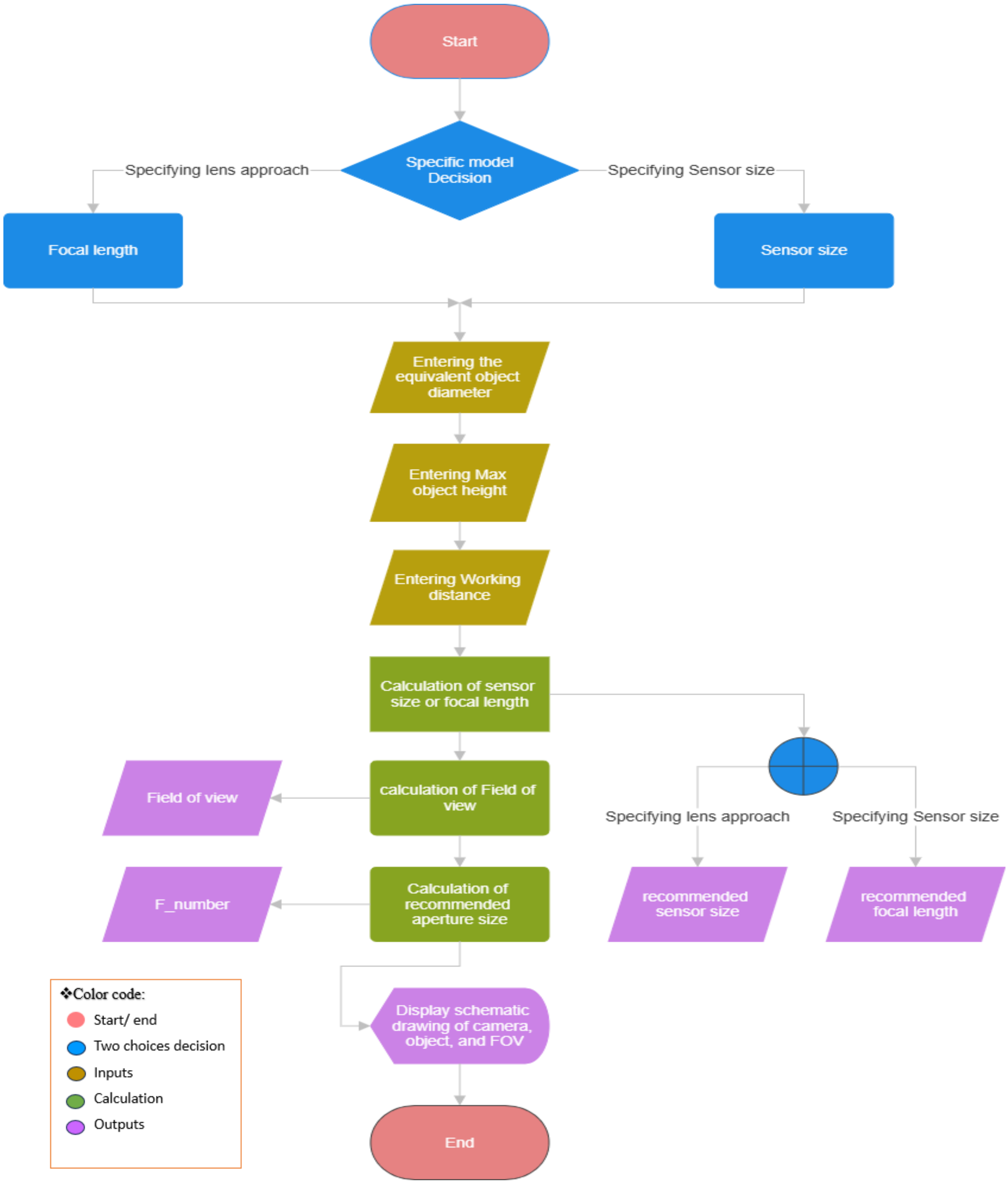
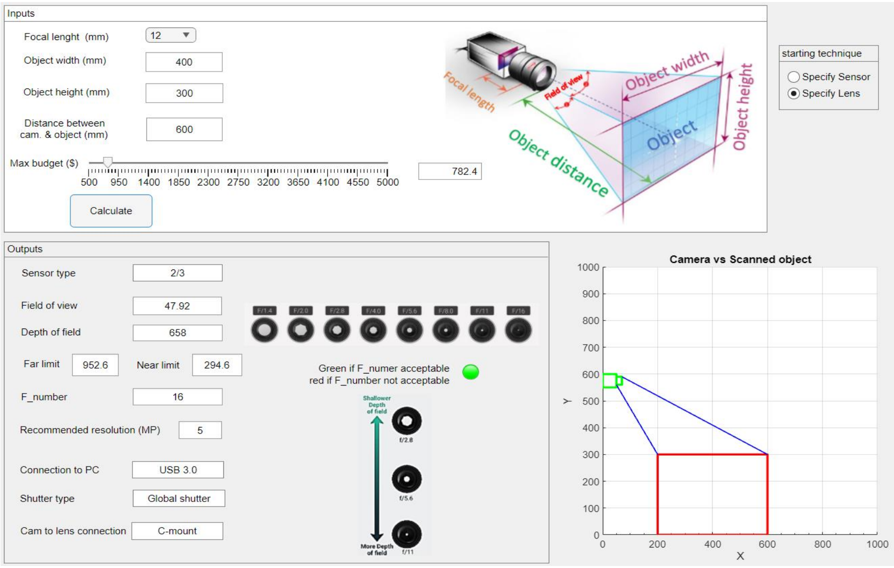


Figure 11. Flowchart of the digitalized camera selection assisting tool

(a) GUI design of the digitalized scanning tool



(b) Recommended camera specifications for specific scanning needs

Figure 12. Graphic User Interface of the developed tool for camera selection

overall dimensions of the scanned object, the standoff distance of the sensing element from the scanned object and the required resolution. The developed tool supports the user with recommendations based on the survey performed by the authors on commercial scanners for any missing entries. Following, the input data is processed based on concepts presented in equations (9) to (14). Finally, the created tools provide the user with all initial camera technical information that may be used later in any camera supplier website to suggest the metrologist a specific camera for being purchased or at least let the metrologist be able to compare between the available scanners to select the most appropriate one for the intended application. As a case study, the authors used the scanning requirements shown in Table 3 to test the developed tool. The developed tool suggested the following camera specifications:

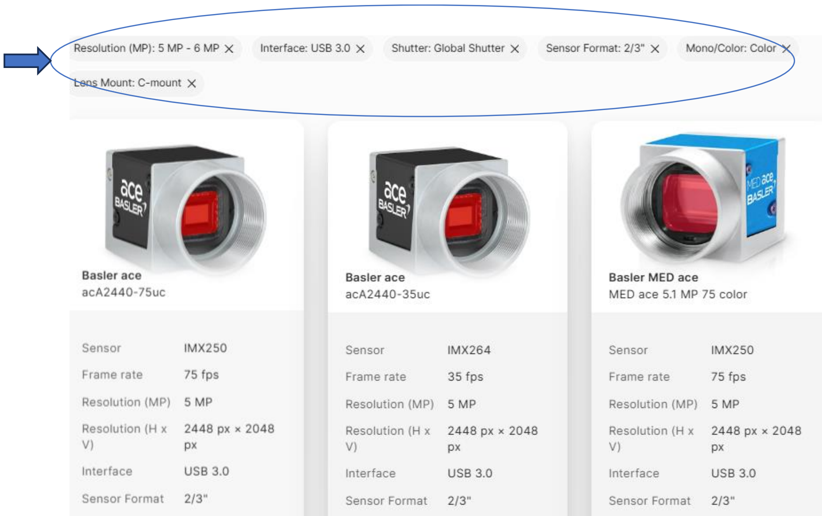
1. Evaluated values:
   a. Sensor size of 2/3".
   b. The field of view of 50^0.
   c. Depth of field of 660 mm.
   d. Field ranges from 295 to 950 mm.
2. Recommended Values
   a. Sensor Resolution 5 MP; mostly recommended for reconstruction applications while considering the requested overall available budget by the user.

Table 3. Proposed scanner specifications

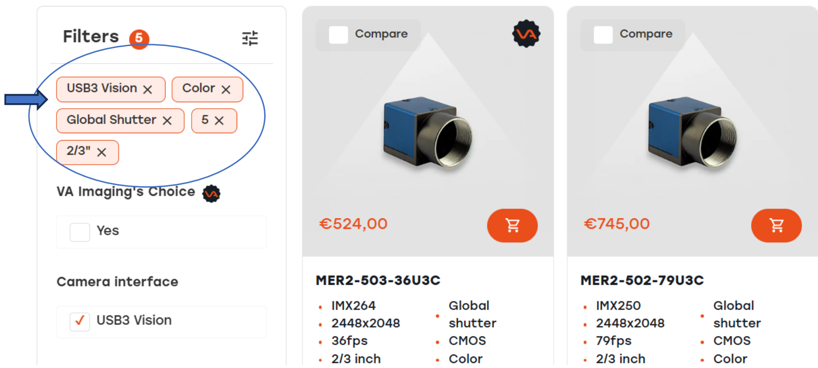
Aspects of scanner	Corresponding imaging parameter	Range
Max length of the scanned object	Maximum scan range	400 mm
Max height of the scanned object	Maximum scan depth	300 mm
Scanner type/ category	Working principle	Photogrammetry “single/ stereo”
Standoff distance	Working distance	approximately 600 mm
Resolution	Resolution	5 MP
Calibration method	Intrinsics	Checkerboard/artifacts

b. Global Shutter, preferred for reconstruction applications.
c. USB 3 connection to processing station; recommended based on the expected volume, includes both the camera and the processing station.
d. C-mount lens connection; recommended based on its popularity in the market.

Finally, the completeness of the output data from the developed digital assisting tool was tested using two different camera vendors, and it was verified that the output data was sufficient for the vendors’ website to suggest a specific camera for the intended use, as shown in Figure 13.



(a) First Commercial Camera Seller (Basler)



(b) Second Commercial Cameral Seller (Daheng)

Figure 13. Testing the resulted data using websites of commercial camera providers

It is worth mentioning that several options were provided by each vendor for the same output data sets to present different frame rates, which is not a key requirement in photogrammetric scanning applications that capture multiple stationary images of the scanned object and do not record a tracking video. In addition, the provided cameras are all industrial-grade cameras that minimize errors and provide better stability, controllability and more accurate results in comparison to ordinary digital cameras, webcams and any other consumer-type cameras.

4. Conclusion

This work developed and presented a digitalized camera selection tool that can close the gap between the metrologist expertise and the knowledge needed for camera selection for specified non-contact scanning needs. The digital tool was developed by encoding the mathematical and physical principles and relations within the optical imaging models using MATLAB. The generated tool was tested using a case study in the form of specified scanning requirements, and the generated output of the tool was tested for completeness using two commercial websites of camera vendors. The final results show that the tool properly exported all data required to specify a specific commercial camera for the metrologist based on his own defined requirements. This tool can be incorporated into wider digitalized systems to help support metrologists from a wider perspective.

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