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تحليل العوامل المؤثرة على تقديرات تحديد المواقع الدقيقة لأهداف التتبع ثنائية الأبعاد

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Analysis of factors influencing precise positioning estimates for 2D fiducial targets

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الملخص:

في العقد الماضي، أدى التقدم السريع في تطبيقات معالجة الصور إلى زيادة أهمية الحصول على صور عالية الجودة. ومع ذلك، يمكن أحيانًا تقييد تعزيز الصور من خلال طرق ما بعد المعالجة من خلال قدرات الكاميرات المتاحة، مثل الدقة وحجم المستشعر و معدل الإطارات في الثانية. بذل الباحثون جهودًا كبيرة لتعزيز أداء الكاميرا وتعظيم فعالية ما بعد المعالجة، مع تحسين دقة الصورة كمجال تركيز مهم بشكل خاص. تهدف هذه الورقة إلى دراسة بعض العوامل التي تؤثر على دقة الكشف ثنائي الأبعاد للأجسام المستهدفة المالية (الأجسام الدائرية الشكل) عند استخدام تعديلين من تحويل الخناق الدائري (**CHT**) (أي طريقة ترميز المرحلة الواحدة وطريقة ترميز المرحلتين). تشمل هذه العوامل تلك المتعلقة بالخصائص الداخلية لخوارزمية تحويل هوف للأشكال الدائرية مثل نطاق نصف قطر البحث والعتبة وشدة اللون. أيضًا، تحلل هذه الورقة تأثير بعض العوامل المرتبطة بطبيعة الجسم الذي يتضمن حدود الشكل وسرعة الهدف. لذلك، يتم استخدام ثلاثة أشكال ثنائية الأبعاد بأقطار متفاوتة: شكل صغير نصف قطره 1 سم، وشكل متوسط نصف قطره 2 سم، وشكل كبير نصف قطره 3 سم. علاوة على ذلك، تم تسليط الضوء أيضًا على تأثير مشكلة الانسداد على نجاح الكشف الشامل للأهداف. تظهر النتائج أن الأهداف المالية ذات الأشكال الدائرية لها دقة فعالة قابلة للتغيير عند سرعات الحركة البطيئة. بالإضافة إلى ذلك، أدى تعديل العناصر الداخلية لصيغتي هوف إلى تغيير طفيف في البكسلات المكتشفة للهدف داخل الصورة، حتى دون حدوث أي حركة. وبالتالي، لم يحدث أي تحول ملحوظ في بيانات تحديد مواقع الجسم المتتبع عبر الإطارات المتتالية.

الكلمات الدالة: تحويل هوف للأشكال الدائرية، ترميز المرحلة، مرحلتين، كثافة الألوان، الدقة المكانية، آلات التحكم الرقمي، أهداف التتبع، الانسداد.

Abstract

In the past decade, the rapid progress in image processing applications has made it increasingly crucial to obtain high-quality images. However, the enhancement of images through post-processing methods can sometimes be restricted by the capabilities of available cameras, such as resolution, sensor size, and FPS. Researchers have made significant efforts to enhance camera performance and maximize the effectiveness of post-processing, with improving image resolution being a particularly important focus area. This paper aims to study some factors affecting the 2D detection accuracy for fiducial target objects (circular shaped objects) when two modifications of Circular Hough transform (CHT) are used (namely Phase coding and two-stage methods). These factors include those related to the internal properties of Circular Hough transform algorithm such as search radius range, thresholding and colour intensity. Also, this paper analysis the influence of some factors connected to the nature of the object which involves the boundaries of the shape and the target's speed. Therefore, Three 2D shapes with varying diameters are being used: a small shape with a radius of 1 cm, a medium shape with a radius of 2 cm, and a large shape with a radius of 3 cm. Moreover, the influence of occlusion problem on the overall detection success for the targets has also been highlighted. The results show that fiducial targets with circular shapes have a changeable effective resolution at slow motion speeds. Additionally, adjusting the internal parameters of the two CHTs resulted in a minor alteration in the detected pixels of the target within the image, even without any movement occurring. Consequently, there was no notable shift in the positioning data of the tracked object across the consecutive frames.

Keywords: Circular Hough transform, Phase coding, Two-stage, Colour intensity, Spatial resolution, CNC machines, Fiducial targets, Occlusion.

I. Introduction

Camera-based systems have gained popularity in numerous motion tracking applications because of their convenient installation process and their capability to function in unprepared environments. These systems rely on extracting image information, such as color and shape properties, to identify the location of objects. Nevertheless, acquiring precise information from images can be challenging as it often necessitates the use of high-resolution cameras, which can be costly in terms of hardware expenses.

In recent years, there has been a significant advancement in image processing applications, leading to a growing need for high-quality images. Camera manufacturers often face limitations in enhancing images, prompting researchers to propose extensive solutions to meet this demand. The term "image resolution" can be complex due to its numerous definitions, but it essentially refers to the smallest measurable detail in a visual presentation [1, 2]. Researchers in optics have defined resolution in relation to the modulation transfer function (MTF). However, MTF has also been utilized to characterize the response of the vision system to any given input [3]. Conversely, in the realm of image processing and computer vision, resolution can be described in three distinct ways: spatial resolution, brightness resolution, and temporal resolution. For the purpose of this work, the term resolution solely pertains to spatial resolution.

The imaging sensors or acquisition devices determine the spatial resolution of an image. Commonly used image sensors, such as charge-coupled devices (CCDs) and complementary metal-oxide-semiconductor (CMOS) active-pixel sensors, are arranged in a two-dimensional array to capture two-dimensional image signals. The size of the sensor primarily determines the spatial resolution of the resulting image. Higher spatial resolution can be achieved by using sensors with a higher density. However, using inadequate detectors in an imaging system can result in aliasing and produce low-resolution images with blocky effects.

To improve the spatial resolution of an imaging system, one approach is to increase the sensor density by reducing the sensor size. However, reducing the pixel size of the sensor also reduces the amount of light incident on each sensor, leading to increased shot noise [4]. Additionally, increasing the sensor density or pixel density of the image raises the hardware cost. Therefore, the hardware limitations on sensor size impose restrictions on the achievable spatial image resolution.[2]

While the image sensor limits the spatial image resolution, the image details (high frequency bands) are also constrained by the optics. Lens blurs, associated with the point spread function of the image sensor (PSF), lens aberrations, aperture diffractions, and motion-induced optical blurring all contribute to the restriction of image details.[5]

Designing and constructing imaging chips and optical components to produce high-resolution images is frequently an impractical approach for many real-world applications, such as tracking cameras, because of the associated high costs. Additionally, increasing the size of the chip to accommodate more pixels leads to a decrease in data transfer rate due to increased capacitance [6]. Apart from the hardware and computational expenses, the resolution of surveillance cameras is also restricted by their speed. In certain applications like satellite imagery, physical constraints make it challenging to utilize high-resolution cameras.

When tracking targets over a large area, it is advisable to use a wide field of view (FOV) camera. However, this approach compromises the resolution, which can be partially mitigated by employing higher resolution vision sensors, even though it may not be a feasible solution. In order to make use of multiple cameras, the relationship between their views must be determined either manually or automatically, but this incurs additional computational costs [7]. If the multiple cameras are assumed to be non-stationary, the object's speed and trajectory must be taken into account to establish correspondence between the cameras.

Another approach to address resolution limitations is to accept image degradation and employ signal processing techniques to enhance the captured images, thereby avoiding excessive computational and hardware costs. These techniques are commonly referred to as super resolution (SR) or resolution enhancement (RE) in the literature [5].

The scope of this paper is to analyze the effect of circular object's boundaries, sizes and motion speed on the its detection accuracy. Also the influence of the internal parameters of the Circular Hough Transform (CHT) on the tracking precision. The search for circles in the image can be controlled by adjusting the search Radius Range (RR), the sensitivity value (S) and edge gradient threshold (T). these parameters can be manually adjusted by the operator. It is worth mentioning that two modified types of CHT will be used during this work which are named "the phase coding method" and "the two stage method".

The paper is organized as follows: Section II shortly describes the principles of feature extraction algorithm used for motion estimation. Section III describes the experimental setup. Section IV presents experimental results and discussion of the outcomes, while Section V concludes the paper.

II. MOTION ESTIMATION ALGORITHM

Motion estimation algorithms, such as the classic Hough transform [8-12] and the phase coding method, have been widely utilized for the detection and fitting of circle objects in images. When employing the Hough transform algorithm as an object detector, it is necessary to convert the images into grayscale. This is due to the nature of the edge function used, which is the canny method.

The canny method is employed to identify two thresholds for detecting strong and weak edges. It outperforms other edge finder methods, such as the Laplacian of Gaussian method. The primary advantage of the canny method is its resilience to noise and its ability to detect true weak edges.

The phase coding method is also extensively employed for circle object detection. One advantage of this algorithm is the ability to control the internal threshold, thereby adjusting the algorithm's sensitivity. This feature is similar to the sensitivity control present in motion detectors utilized in home security systems. Unlike the Hough transform, the conversion of RGB images to grayscale is not necessary when using the phase coding method. However, the results remain consistent in both cases.

The phase coding method, compared to the two-stage method, offers several advantages in circle detection. It can detect more circles even at lower levels of sensitivity. Additionally, it exhibits enhanced resilience to noise. On the contrary, the two-stage method, although slower, can also detect circles but with slightly less accuracy in noisy environments.

Furthermore, both algorithms have a parameter called 'Edge Threshold' which determines the minimum gradient value that a pixel must possess in order to be classified as an edge pixel and be taken into account during the computation process. A higher value of this parameter (closer to 1) only includes strong edges with higher gradient values, while a lower value (closer to 0) is more lenient and encompasses weaker edges with lower gradient values.

Considering the advantages of the phase coding method, it will be utilized as the motion detector for circle objects in this experiment. Therefore, the term Circle Detection Method (CDM) specifically refers to the phase coding method.

III. Experimental Setup

A The Small 3-axis CNC milling machine, equipped with linear scale feedback on all axes, was utilized for the experiment. This machine (refer to Fig. 1) enabled precise motion control with an accuracy of up to +/- 5 μm/m. The programming restricted the machine's movement to the horizontal axis (X axis) only. The objects under observation were placed on the machine bed, which was programmed to shift along the X axis at a speed of 2000 mm/min. The machine spindle was equipped with a Samsung ST200F camera, which is a cost-effective and widely used camera for personal use, to capture images. The camera was positioned at a distance of 390 mm from the objects. With an effective horizontal resolution of 1 pixel/0.3 mm, this camera ensured clear and detailed images.

During the process of detecting the centres and radii for a moving object, some inaccuracies might occur. This paper aims is to analyse some factors that could influence the information accuracy of the tracked object. The following three factors will be analysed:

- The nature of the object: shape and the motion speed.
- The object detection algorithm: the internal algorithm parameters such as thresholding values, and sensitivity.
- Image properties: colour intensity (RGB values).
- Partial occlusion problem

The approach taken in this work includes the utilization of three distinct targets (Fig. 2): a small target measuring 1cm in radius, a medium target that is a plain shape without edges and has a radius of 2cm, and a large target with a radius of 3cm. Two different motion speeds used with the objects, high speed (2000mm/min), and low speed (18mm/min). Moreover, two popular algorithms have been used for detecting circular objects which are Phase-coding method and a classic Hough transform (namely two-stage method) in order to see their efficiency and accuracy in detecting objects.

Both experiments were conducted on the Cincinnati machine, the machine (see Fig. 1) was used to attain precise measurements of up to +/- 5 μm/m, and was specifically programmed to operate along the horizontal x-axis.

The horizontal resolution=(390×1000)/1280=304.6875 (μm)/pixel

Therefore, the conversion from image coordinates (pixels) to world coordinates (mm) as follow:

1 pixel=0.3046875 mm

IV. Results and Discussions

This section will examine the performance of two popular object detection algorithms will be analyzed, a classic Hough transform (namely, two stage method) and Phase coding method will be used to detect circular objects differing in the shape borders and radius (Fig. 2).

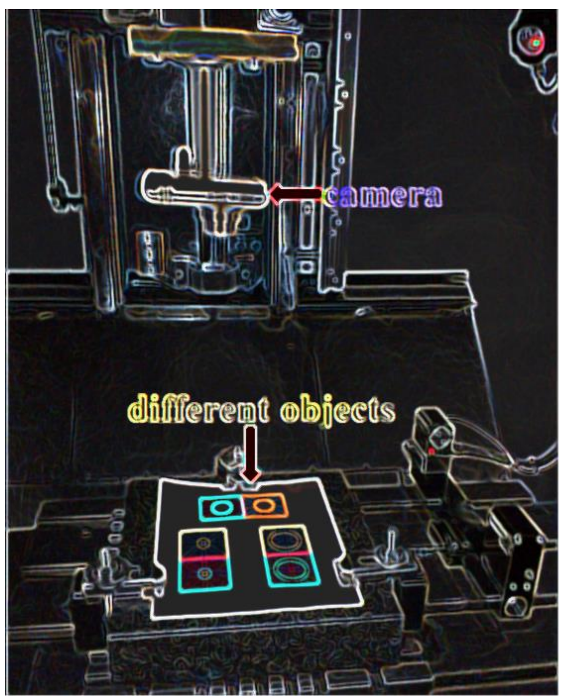

Fig. 1: Experimental configuration.

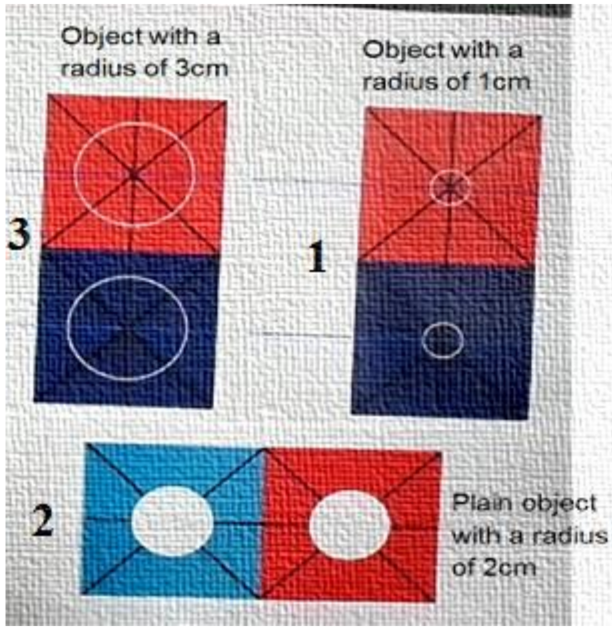

Fig. 2: Board of objects.

Fig. 3 and Fig. 4 show the performance of two algorithms in detecting fast moving targets (2000mm/min). The algorithms performed best when the object had no edges (object 2). When the objects underwent horizontal shifts, the phase coding method demonstrated a change in the object's radius during its motion. On the other hand, the two-stage algorithm failed to detect any changes in the radius values. This can be attributed to the detector's sensitivity to the accurate configuration of thresholding parameters. In comparison, the phase coding method exhibited higher sensitivity to changes in the edges compared to the two-stage technique. Moreover, Table 1 and Table 2 clearly indicate that the sensitivity of the two-stage technique in detecting variations in object radius is significantly lower compared to the performance of phase coding.

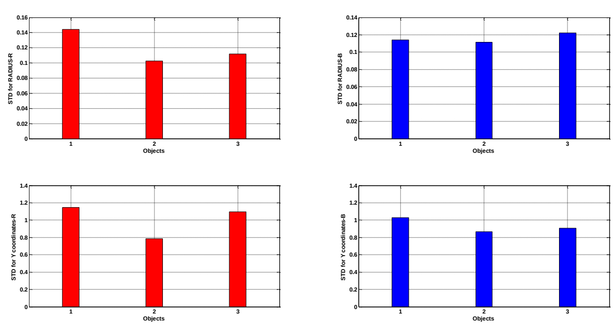

Fig. 3: Standard deviation for the three objects (Phase coding method).

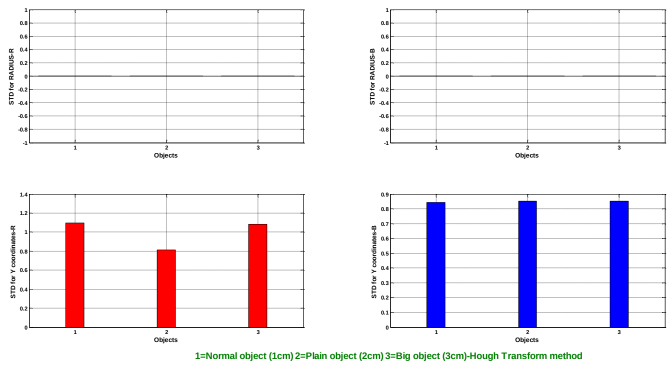

Fig. 4: Standard deviation for the three targets (Two-stage method).

Table 1: Standard deviation for the three targets (Phase coding method).

Method	Objects	STD RR	STD BR	STD YR	STD YB
Phase Coding method	1	0.145	0.114	1.148	1.028
	2	0.103	0.111	0.786	0.867
	3	0.112	0.122	1.098	0.908

Table 2: Standard deviation for the three objects (Two-stage method).

Method	Objects	STD RR	STD BR	STD YR	STD YB
Two Stage method	1	0	0	1.098	0.843
	2	0	0	0.813	0.853
	3	0	0	1.082	0.853

Fig. 5 and Fig. 6 show that the phase coding method detects the outer borders of the object, and the classic Hugh transform method detects the inner borders, the difference between the two algorithms in the way of detecting edges led to a considerable difference in the obtained data from the objects (such as the radius values). Moreover, it is evident from Fig. 7 and Fig. 9 that the difference in the detected radius value for the small and big objects by using the two techniques is around 3 pixels (0.9 mm). However, in the case of the plain object that having no edges (Fig. 8), the difference in the detected radius value is around of 0.4 pixels (0.12 mm).

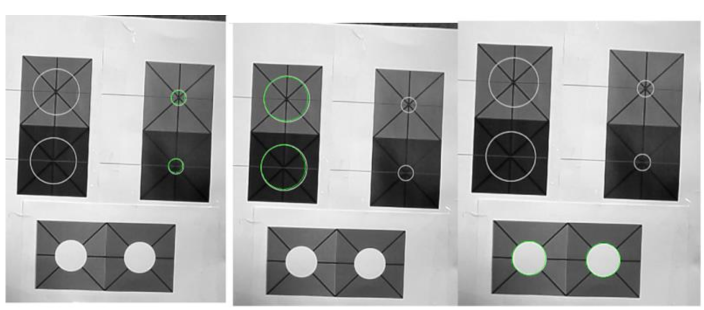

Fig. 5: Two-stage detector.

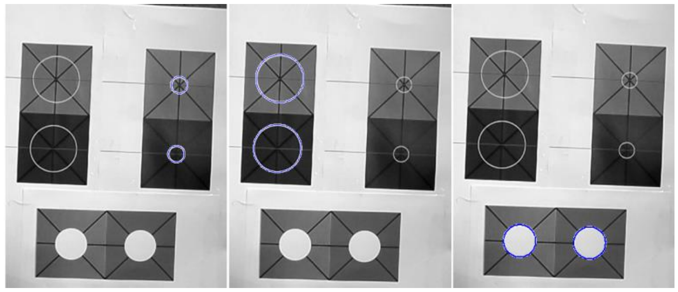

Fig. 6: Phase coding algorithm.

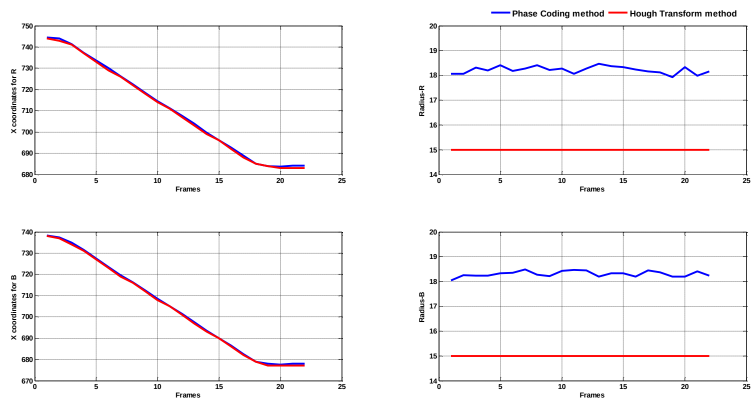

Fig. 7: Comparison between the performances of two algorithms on small object detection.

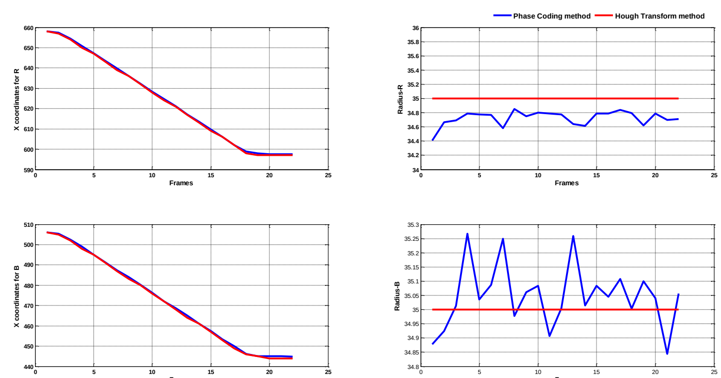

Fig. 8: Comparison between the performances of two algorithms on medium (plain) object detection.

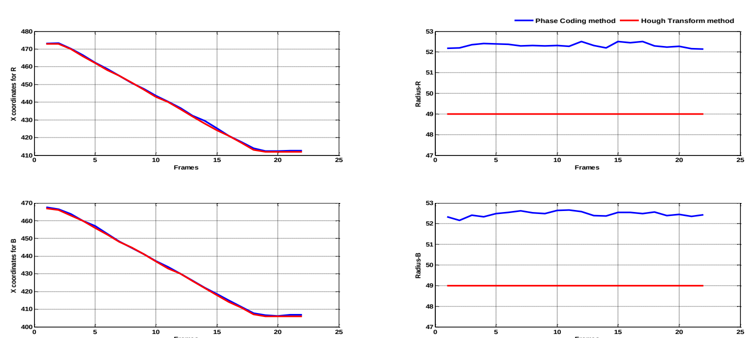

Fig. 9: Comparison between the performances of two algorithms on big object detection.

The second part of the experiment is to examine how altering the speed of motion affects the effective spatial resolution of the tracked target. It is important to note that when the target's motion speed is high, any changes in pixel resolution cannot be observed (**Fig. 10**-upper part). However, when the motion speed is low, we can observe changes in pixel resolution, which consequently impact the effective spatial resolution (**Fig. 11**) The Figure provides evidence that the circular shapes exhibit varying effective resolution at low motion speeds.

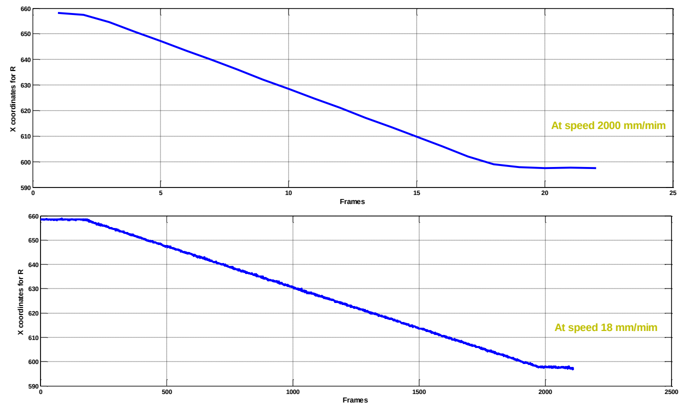

Fig. 10: Object motion at high speed (upper), and at low speed (down).

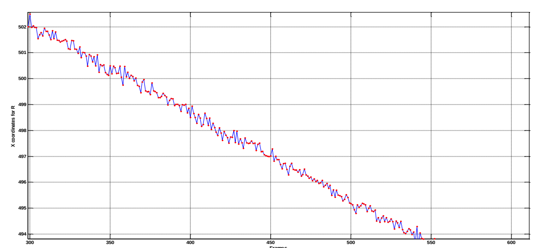

Fig. 11: Object motion at low speed.

Fig. 12 demonstrates how, like most sensors, the readings fluctuate over time, even when the object motion was controlled precisely by an axis controller. It is imperative for researchers to provide a mathematical justification that can reconcile the discrepancy between the theoretical and observed resolutions and establish the correlation between variations in the effective pixel resolution and object shape.

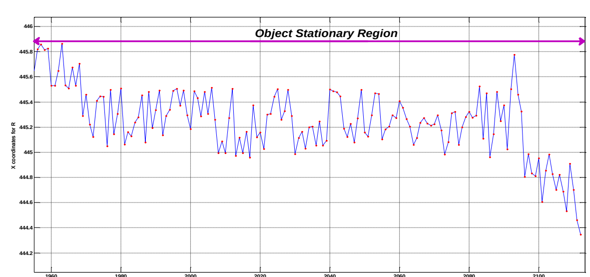

Fig. 12: Object stationary region.

The internal parameters of the detection algorithm also affect the effective resolution, Fig. 13 shows that changes in these internal parameters of the algorithm, such as the estimated radius range, sensitivity value and thresholding, results in a variation in the detected pixels of the target in the image, even in the absence of any motion applied to the target.

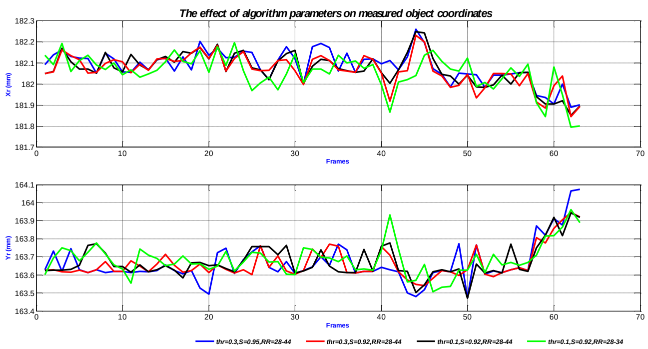

Fig. 13: The effect of algorithm parameters on measured object coordinates.

The changes of the effective pixels in the object also can be notified when the colour histogram applied on six consecutive frames taken during the stationary period of the object (see Fig. 14, Fig. 15 and Fig. 16). The results showed that the number of pixels that represent each colour changed.

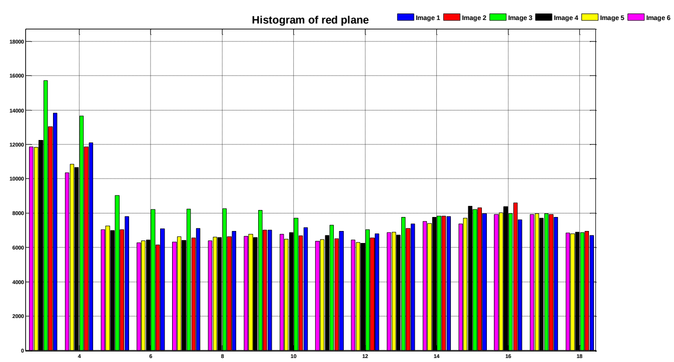

Fig. 14: Histogram of red plane.

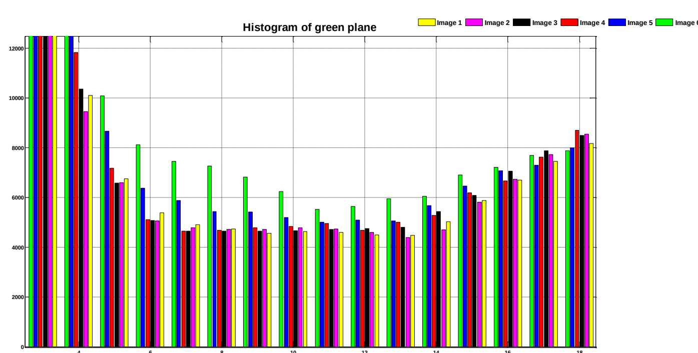

Fig. 15: Histogram of green plane.

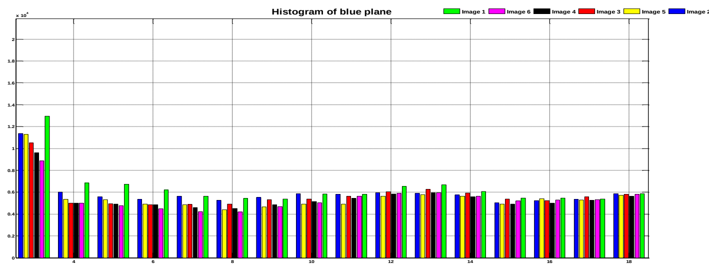

Fig. 16: Histogram of blue plane.

In order to confirm the change in the effective spatial resolution, high resolution cameras will be used in the future for tracking the robot, one of the reasons behind using high resolution cameras is to find the relationship between the theoretical resolution and the practical resolution.

The occlusion problem can cause a decrease in the performance of the object detection process as it introduces false color information to certain pixels in the depth color images. Despite of the fact that Circular Hough Transform (CHT) has the capability to detect objects that are partially occluded in the images, especially when the detection task is performed in unprepared environment.

In this part of the experiment, the objects have been partially occluded with a percentage of 25%, 50% and 75%. The experiment has been iterated 10 time under different occlusion scenario. ST200F camera was mounted on the machine spindle, positioned 500 mm away from the board of the objects. The CNC machine axis wasn't programmed to provide any horizontal or vertical displacements. It's worth mentioning that the objects were separated via image cropping commands in Matlab and no interpolation processes were performed during this work.

Table 3 shows that the objects with radius of 2 mm possess higher success rate compared to small and big objects, they are robust to the changes in the scene because of its white background. The results showed the successful detection process is more affected by the strong edges for the object rather than its big radius values.

Table 3: Object occlusion experiments.

Type of object	Occlusion percentage (%)	Success rate (%)
1	25%	0%
1	50%	12.3%
1	75%	38.7%
2	25%	22.5%
2	50%	54.3%
2	75%	88.6%
3	25%	17.7%
3	50%	45.6%
3	75%	89.2%

V. Conclusion

Different factors affecting the pixel resolution and the overall detection accuracy have been analysed, the results showed that effective pixels in the object changed leading to changes in the effective spatial resolution. Despite the absence of any applied motion scenario to the target, variations in the algorithm's internal parameters, including the chosen search radius range, sensitivity value, and thresholding, result in alterations to the detected pixels of the target within the image. Therefore, a mathematical explanation must be offered by researchers to connect the theoretical and practical detected resolution, as well as find the relationship between changes in the effective pixel resolution and the target's shape. For future work, a tracking system combining of three high resolution cameras will be installed and used instead of a single standard camera for tracking and detecting the location of the object. The influence of the inner Hough parameters on the detection accuracy of spherical 3D targets can be suggested for further study.

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