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ASSESSING COLLABORATIVE ROBOT RELIABILITY FOR COLOUR SORTING UNDER VARYING LIGHTING CONDITIONS

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Abstract: This research aimed to evaluate the reliability of a collaborative robotic system for sorting coloured aluminium pucks under varying lighting conditions. The experimental workstation was designed and implemented to assess the reliability of sorting. The system employs a FANUC CR-7iA/L robot with an iRVision 2D camera for colour recognition, working with inductive and optical sensors. A custom control program integrates subroutines for colour detection, puck manipulation, and conveyor control. Test results indicate optimal recognition performance in the 550–740 lx range out of the total 97–1024 lx spectrum. This solution offers efficient automation, high safety, and straightforward adaptability to diverse production tasks.

Key words: Collaborative robotics, Colour recognition, iRVision 2D, Lighting conditions, Robot programming.

1. INTRODUCTION

Reliable machine vision constitutes a crucial enabling technology within Industry 4.0, underpinning autonomous inspection, traceability, and adaptive control across interconnected production lines. [1], [2], [3] Nevertheless, even advanced colour-based vision systems exhibit marked sensitivity to ambient light fluctuations, compromising the fidelity of downstream sorting, assembly, and quality assurance operations.

To situate the present study of machine-vision reliability under variable illumination within the extant body of knowledge, we conduct a systematic literature review that synthesises empirical findings on how lighting conditions influence colour-classification accuracy. A structured overview of selected scientific publications relevant to the topic follows.

The authors of the article “A systematic literature review of computer vision applications in robotised wire harness assembly” [4] provide an in-depth exploration of computer vision applications in robotised wire harness assembly. They examine the principles underlying the

applied computer vision approach, including its integration with machine learning techniques; however, illumination conditions were not addressed.

In the article “Copy and Paste Augmentation for Deformable Wiring Harness Bags Segmentation,” [5] lighting conditions relevant to machine vision are mentioned, but only in general terms and without detailed specification or experimental analysis.¶

The article “Investigating Research Trends in Computer Vision for Food Quality Control: A Bibliometric Approach” [6] addresses overarching trends in computer vision research but does not provide specific insights into the reliability or influence of lighting conditions.

The research paper “A Framework for Planning Underwater Hull Inspections Based on Computer Vision and Degradation Assessment” [7] focuses on applying computer vision in particular underwater environments. Although it acknowledges challenging lighting conditions, these are not described or analysed in detail.

The research paper “Tracking and Mapping in Medical Computer Vision: A Review” [8] acknowledges the importance of lighting conditions, but primarily focuses on lighting

models designed to mitigate the effects of disruptive or adverse lighting phenomena.

None of the reviewed scientific articles explicitly focuses on lighting conditions or systematically assesses the reliability of machine vision systems regarding illumination-related factors. To elucidate this deficiency, the present study quantifies the influence of illumination intensity on the classification accuracy of a FANUC CR-7iA/L cell equipped with an iRVision 2D camera system.

2. EXPERIMENTAL WORKPLACE

This paper presents the design and implementation of an experimental workstation intended for the manipulation and precise placement of colored aluminum pucks into silon pallets, each featuring uniquely designed color differentiations (see Fig. 1). The workstation comprises a mobile block cell outfitted with a conveyor belt, trays for four different colored pucks, and a robotic system that includes a robot control unit, a robotic arm, and a control pendant. The robotic arm is equipped with a collaborative gripper and a camera capable of recognising various colour shades. The Fanuc CR-7iA/L collaborative robot exemplifies a series of collaborative robotics, with a payload capacity ranging from 3 kg to 35 kg. Key specifications of this robot include a payload capacity of 7 kg, a reach of 911 mm, and a repeatability of 0.01 mm. A six-axis robotic arm can achieve up to 1000 mm/s speeds under optimal safety conditions.



Fig. 1. Experimental workplace

2.1 Basic elements of the robotic system

The robotic arm has a force sensor at its base, integrated into a six-axis mechanism. Movement is facilitated by servo motors positioned at each joint. A Schunk Co-act EGP-C 40 N-N-ASSISTA collaborative gripper and a Fanuc SC130EF2 camera are mounted at the wrist. The fingers of the collaborative gripper are crafted from brass and explicitly designed to grasp round pucks with a diameter of 50 mm (see Fig. 2). All communications between the control unit and the gripper, as well as the camera, are conducted through connectors located on the forearm.



Fig. 2. Gripper of the robot

2.2 Used sensors and camera system

Based on the knowledge of the principles of sensing systems, sensor solutions were selected to simulate human sensory perception at the experimental site.

FANUC's iRVision is a fully integrated visual sensing system that enables robots to see and control production setups faster, more innovative and more reliable way, increasing overall flexibility and efficiency on the jobsite. For the experimental workstation, a colour variant was installed on the wrist. The setup was done using a web browser by connecting directly to the control unit via an Ethernet cable. The system can also be set up in the control pendant.

3. PROGRAM DESIGN

The program comprises various subroutines in certain situations and under certain conditions. The subroutines contain data from the vision processes and, thanks to them, can perform the tasks in the prescribed quality in terms of positioning and colour distribution. In this chapter, the structure of the programs (Fig.

3) and the creation of vision processes are shown.

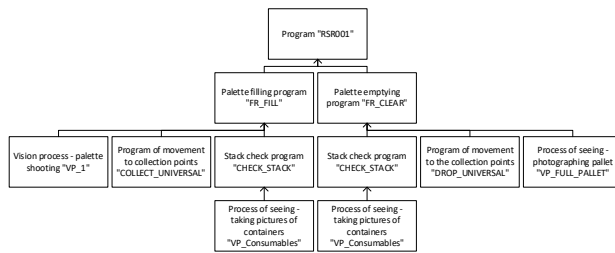


Fig. 3. Structure of the main program

The iRVision 2D camera system is the cornerstone of all the subroutines, the definition of the pallet position vision process, and the process of recognising tray positions by colour. Setting up both processes involves the same steps with only different values, so only the palette vision and colour panel recognition process is described in this subsection. The basic settings of the vision process define the camera used and the number of tiles searched. The other specifications are unimportant for our demonstration (Fig. 4).

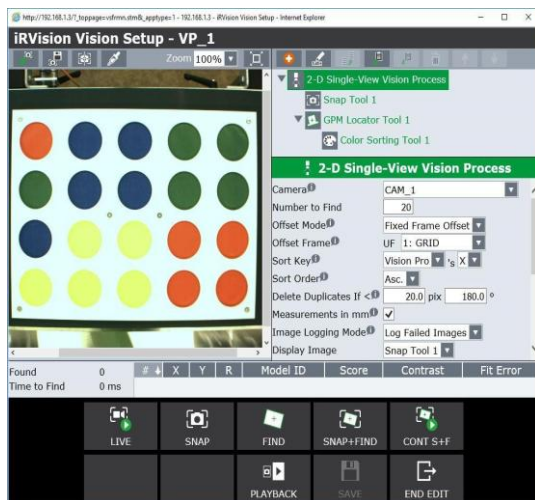


Fig. 4. Basic settings of the vision process

In the next step, the shape the process seeks is learned. The goal is to know the circle that is of the best quality out of all 20 circles, so the circle with the smallest distance from the center of the palette and the highest possible difference between white and gray is selected (Fig. 5). Due to the shooting from one position, all other circles appear deformed, so it is necessary to introduce shape and size tolerances in the settings. Subsequently, the

"snap + find" button is used to verify that the positions of all 20 circles are captured (Fig. 6).

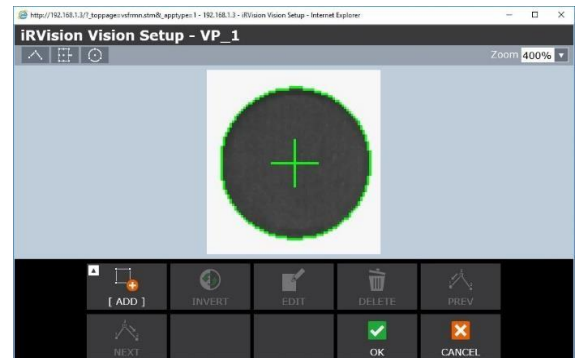


Fig. 5. A learned shape

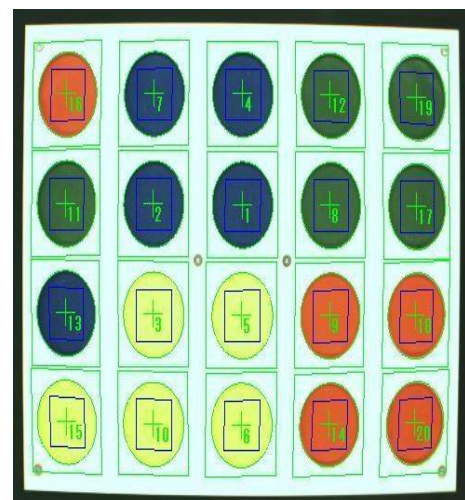


Fig. 6. Checking the capture of all rings

The final step of this process is to identify the colours within all the circles. The four colours that are inside the most visible circles are defined. Their hue ranges on a scale from red 0 to purple 360 (Fig. 7). Due to imperfect illumination, each area exhibits a colour of different shades, although in reality it is the same. This was resolved by specifying a tolerance by which the hue of the colour can vary. Since the colours blue, green, red and yellow are located at the largest spacing on the colour spectrum, it was possible to define a high tolerance and thus ensure that all four colours could be easily distinguished. All colours were assigned to individual sample colour IDs (Fig. 8). Thus, the vision process output is the circle's position and colour ID. This information is still used in the motion subroutines.

#	Color	ID	Hue	Saturation	Intensity
1		1	211.6	60.4	62
2		2	111.5	46.2	84
3		3	15.7	79.6	119
4		4	71.7	54.0	232

Fig. 7. Shade of learned colours

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1		211.87	2.61	1	0.27
2		212.18	2.73	1	0.58
4		212.60	2.68	1	1.00
7		213.04	2.37	1	1.44
13		212.86	2.75	1	1.26
8		116.87	5.02	2	5.39
11		118.82	5.24	2	7.34
12		116.21	5.06	2	4.73
17		115.94	4.62	2	4.46
19		114.48	4.69	2	2.99
9		16.38	0.80	3	0.70
14		15.37	0.73	3	0.29
16		15.58	0.94	3	0.08
18		15.21	0.79	3	0.45
20		14.42	0.73	3	1.25
3		73.31	0.62	4	1.65
5		73.36	0.60	4	1.70
6		71.99	0.50	4	0.33
10		71.93	0.50	4	0.26
15		71.83	0.50	4	0.17

Fig. 8. Assigning IDs to captured colours

As well as for the positions on the palette, it was necessary to create a visual scanning process for the trays that verifies the position of the colours in all four trays. This process checks both the left and right pairs of trays. The premise of this process is that each tray always contains only pucks of the identical colour Fig. 9 and Fig. 10.



Fig. 9. Left pair of magazines

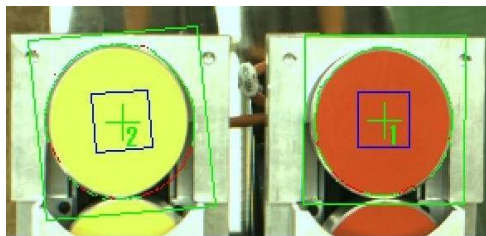


Fig. 10. Right pair of magazines

4. SYSTEM RELIABILITY TESTING

The entire system and its smooth operation depend not only on the design of the gripper fingers, pucks, pallets, dispensers, and proper

programming, but also on the lighting conditions under which the camera system operates.

4.1 Testing different pallet configurations and dispenser swaps

The program was run with each of the ten variations of coloured patch layouts on the pallet (Fig. 11). In all cases, the system could correctly recognise the colours and fill the pallet with 100% accuracy.

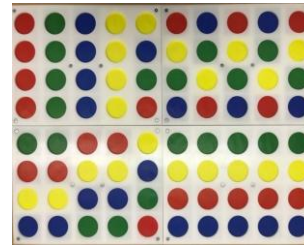


Fig. 11. Examples of Patch Layout Variants on Pallets

Several experiments were conducted involving swapping specific colour positions in sure dispensers. In the example below, the blue dispenser was swapped with the yellow one, and the green with the red one (Fig. 12). Even in this case, the system was always able to respond to the change and adjust its pick-up points accordingly to fill the pallet with pucks of the correct colours.

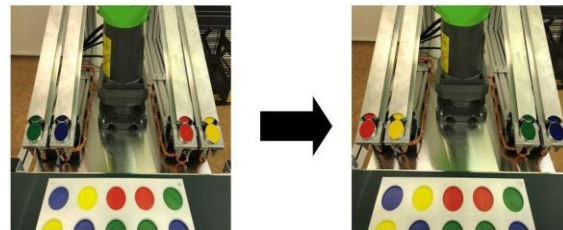


Fig. 12. Dispenser Swapping

4.2 Experiments with light intensity adjustment at the centre of the pallet

The experimental workstation is in a windowless room, illuminated by three rows of fluorescent lights. This section tests the system's ability to correctly recognise colours under all possible combinations of switched-on or off light rows. Additionally, experiments with external lighting were carried out. In all variants, light intensity at the center of the pallet was measured using a lux meter (Fig. 13). For a better understanding of this section, the following image shows the individual light

rows labeled with indices (Fig. 14). If a light row index appears in the experiment name, it means that the corresponding row of lights was turned on in that particular experiment.



Fig. 13. Lighting



Fig. 14. Lux meter

Experiment 1 – 2 – 3

When all three rows were turned on, the light intensity was measured at 673 [lx]. The results of the captured colour shades of individual patches can be seen in the following table (Fig. 15). In the subsequent measurements, deviations in captured colour shades from the standard results (with all light rows on) can be observed.

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1	Dark Blue	211.33	2.78	1	0.26
4		211.77	2.91	1	0.17
9		212.42	2.58	1	0.82
11		212.89	2.53	1	1.29
12		212.51	2.77	1	0.91
5	Dark Green	116.67	4.91	2	5.18
10		115.92	5.18	2	4.44
14		118.93	5.21	2	7.45
16		116.05	4.81	2	4.56
19		114.17	4.76	2	2.69
8	Orange	15.44	0.78	3	0.22
13		14.85	0.77	3	0.82
17		14.80	0.75	3	0.86
18		15.26	0.85	3	0.41
20		14.32	0.80	3	1.35
2	Yellow	72.47	0.58	4	0.80
3		72.38	0.54	4	0.71
6		71.23	0.50	4	0.43
7		71.11	0.50	4	0.55
15		71.06	0.50	4	0.60

Fig. 15. Experiment: Standard Lighting

Experiment 2 – 3

In this experiment, lighting conditions were worsened by turning off the first row of lights. The light intensity was measured at 583 [lx]. The results of the captured colour shades of the

individual patches are shown in the following table (Fig. 16).

Experiment 1 – 2

In this experiment, lighting conditions were worsened by turning off the third row of lights. The light intensity was measured at 423 [lx]. The results of the captured colour shades of the individual patches are shown in the following table (Fig. 17).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1	Dark Blue	211.14	2.77	1	0.45
3		211.61	2.95	1	0.01
8		212.16	2.70	1	0.56
11		212.58	2.64	1	0.97
12		212.27	2.92	1	0.67
2	Dark Green	117.71	5.06	2	6.23
10		117.06	5.36	2	5.58
13		120.12	5.42	2	8.64
15		117.04	5.05	2	5.55
18		115.11	5.05	2	3.62
7	Orange	15.36	1.16	3	0.31
14		14.99	1.16	3	0.67
16		14.92	1.14	3	0.74
19		15.42	1.22	3	0.24
20		14.39	1.18	3	1.28
4	Yellow	71.00	0.50	4	0.66
5		71.03	0.50	4	0.63
6		70.07	0.50	4	1.60
9		70.02	0.50	4	1.65
17		69.99	0.50	4	1.67

Fig. 16. Experiment 2 – 3

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
3	Dark Green	118.97	5.90		
9		117.11	6.16		
11		121.52	6.34		
13		118.17	5.94		
17		114.89	6.39		
1	Dark Blue	212.71	3.32	1	1.12
2		212.23	3.22	1	0.63
4		213.12	3.04	1	1.53
8		213.52	2.84	1	1.92
10		213.59	3.38	1	1.99
5	Orange	15.30	1.30	3	0.36
12		14.44	1.36	3	1.23
14		14.83	1.32	3	0.83
15		15.44	1.37	3	0.23
18		14.06	1.40	3	1.61
6	Yellow	57.05	1.75	4	14.61
7		55.70	1.66	4	15.96
16		56.77	1.83	4	14.89
19		56.40	1.70	4	15.26
20		57.65	1.76	4	14.01

Fig. 17. Experiment 1 – 2

Experiment 1 – 3

In this experiment, lighting conditions were worsened by turning off the second row of lights. The light intensity was measured at 381 [lx]. The results of the captured colour shades of the

individual patches are shown in the following table (Fig. 18).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1		211.82	4.26		
2		110.75	6.65		
3		212.22	4.51		
5		213.50	4.25		
6		50.71	1.52		
7		49.73	1.49		
8		48.94	1.44		
9		111.61	7.13		
10		50.19	1.52		
11		213.99	4.13		
12		212.72	4.29		
14		112.65	7.11		
15		109.86	6.66		
18		110.08	6.87		
19		51.03	1.61		
4		14.57	1.29	3	1.10
13		14.50	1.25	3	1.17
16		14.14	1.25	3	1.52
17		14.04	1.38	3	1.63
20		13.97	1.29	3	1.70

Fig. 18. Experiment 1 - 3

Experiment 1

In this experiment, lighting conditions were worsened by turning off the second and third rows of lights. The light intensity was measured at 97 [lx]. The results of the captured colour shades of the individual patches are shown in the following table (Fig. 19).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1		217.83	9.34		
2		218.17	9.52		
3		93.72	9.56		
4		46.94	3.24		
5		13.74	3.64		
6		47.18	3.22		
7		219.07	9.47		
8		218.51	9.02		
9		96.62	11.73		
10		46.32	3.22		
11		219.90	9.83		
12		46.68	3.21		
13		95.26	9.76		
14		13.05	3.96		
15		91.57	10.81		
16		13.35	3.73		
17		13.03	3.65		
18		92.21	10.26		
19		46.76	3.38		
20		12.58	3.97		

Fig. 19. Experiment 1

Experiment 2

In this experiment, lighting conditions were worsened by turning off the first and third rows of lights. The light intensity was measured at 319 [lx]. The results of the captured colour shades of

the individual patches are shown in the following table (Fig. 20).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
2		120.64	6.37		
7		118.61	6.78		
8		213.60	3.70		
9		123.36	6.53		
11		120.00	6.56		
14		116.70	7.15		
1		212.59	3.67	1	0.98
3		212.02	3.57	1	0.42
5		212.85	3.39	1	1.25
6		213.22	3.30	1	1.63
4		15.50	1.50	3	0.16
10		14.45	1.55	3	1.21
12		14.98	1.48	3	0.69
13		15.82	1.59	3	0.14
15		14.03	1.63	3	1.64
16		60.34	1.95	4	11.32
17		60.92	1.83	4	10.74
18		59.64	1.90	4	12.03
19		58.83	1.88	4	12.83
20		60.19	1.89	4	11.47

Fig. 20. Experiment 2

Experiment 3

In this experiment, lighting conditions were worsened by turning off the first and second rows of lights. The light intensity was measured at 265 [lx]. The results of the captured colour shades of the individual patches are shown in the following table (Fig. 21).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID↓	Hue Error
1		212.35	4.88		
2		212.65	5.00		
3		110.92	7.63		
5		213.85	4.97		
6		111.74	8.61		
7		214.22	4.90		
8		213.23	4.87		
10		113.01	8.12		
11		110.18	8.01		
13		110.08	8.09		
16		50.70	1.70		
17		50.22	1.72		
18		48.90	1.61		
19		51.20	1.79		
20		49.63	1.63		
4		14.55	1.38	3	1.12
9		14.58	1.37	3	1.09
12		14.02	1.38	3	1.65
14		13.87	1.53	3	1.80
15		13.88	1.43	3	1.79

Fig. 21. Experiment 3

4.3 Experiment with LED Illumination Enhancement

This experiment enhanced standard lighting conditions using an LED light source. The measured illumination intensity at the centre of the pallet was 740 lx. The results of the detected

colour shades on individual patches are presented in the following table (Fig. 22).

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID	Hue Error
2		210.05	2.66	1	1.55
4		211.56	2.53	1	0.04
9		212.17	2.34	1	0.57
11		212.79	2.23	1	1.20
12		212.38	2.66	1	0.78
5		120.42	4.75	2	8.93
10		118.90	4.85	2	7.42
14		120.92	4.98	2	9.44
16		118.81	4.49	2	7.33
19		116.76	4.55	2	5.27
8		17.04	0.94	3	1.37
13		15.28	0.76	3	0.38
17		15.39	0.77	3	0.27
18		15.51	0.87	3	0.15
20		14.44	0.78	3	1.22
1		74.31	0.70	4	2.65
3		73.84	0.67	4	2.18
6		72.29	0.50	4	0.62
7		72.06	0.50	4	0.40
15		71.85	0.50	4	0.18

Fig. 22. Experiment with LED Illumination Enhancement

4.4 Experiment with Fluorescent Lamp Illumination Enhancement

In this experiment, the standard lighting setup, composed of three rows of lights, was supplemented by an additional fluorescent lamp. The measured illumination intensity ranged between 832 lx and 1024 lx. Under these conditions, the system encountered difficulties in identifying the shape of yellow patches, which were perceived as white (Fig. 23). The results of the detected colour shades on individual patches are summarised in the following table (Fig. 24).

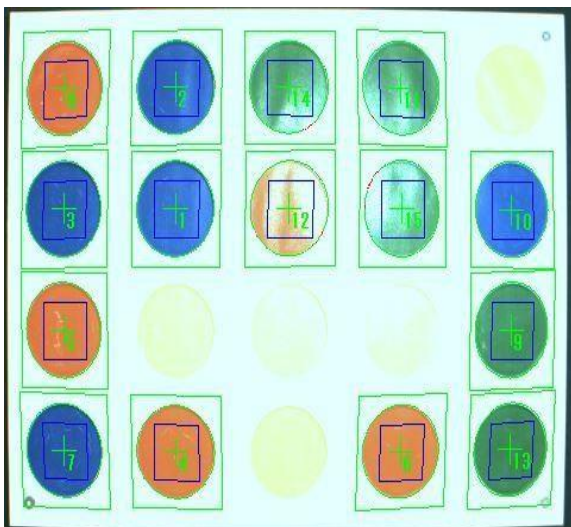


Fig. 23. Experiment with Fluorescent Lamp Illumination Enhancement (1)

#	Measured Color	Hue Mean	Hue Std. Dev.	Color ID	Hue Error
7		217.52	1.58	1	5.93
3		217.36	2.06	1	5.76
10		217.14	0.87	1	5.54
2		216.95	1.55	1	5.35
1		216.07	1.54	1	4.47
15		162.35	10.78		
11		152.28	7.56		
14		150.20	9.50		
9		144.56	3.08		
13		140.16	3.42		
12		98.87	57.76		
6		24.02	1.48	3	8.35
4		22.65	1.78	3	6.98
5		21.28	2.65	3	5.61
8		19.86	2.01	3	4.20

Fig. 24. Experiment with Fluorescent Lamp Illumination Enhancement (2)

5. DISCUSSION

The results presented in the following table demonstrate that the system exhibits significant limitations under variations in lighting conditions (Table 1). In some instances, it failed to identify the correct colours and could not detect the shape of the patches due to minimal contrast between the patch and its surroundings. This issue can theoretically be addressed by increasing the tolerance levels for contrast, shape, and colour differences. However, such an approach is generally unsuitable for industrial applications, where components often require precise geometric definition, and any increase in tolerance may compromise overall system accuracy. Based on the measurements, it can be confidently asserted that illumination quality is a critical factor in accurate colour identification using vision-based systems.

Table 1

Measured Colour Identification Outcomes at Various Light Levels

Lighting variant	Illumination intensity [lx]	Number of correct detections				Total of correct detections	Percentage [%]
		Blue	Green	Red	Yellow		
1 2 3	673	5	5	5	5	20	100
2 3	583	5	5	5	5	20	100
1 2	423	5	0	5	5	15	72
1 3	381	0	0	5	0	5	25
1	97	0	0	0	0	0	0
2	319	4	0	5	5	14	70
3	265	0	0	5	0	5	25
1 2 3 + LED	740	5	5	5	5	20	100
1 2 3 + LAMP	832	3	2	5	2	12	60
1 2 3 + LAMP	1020	5	0	4	0	9	45

Figure 25 illustrates the illumination intensities applied in each experimental setup. Nine lighting configurations were tested, resulting in nine distinct illuminance levels ranging from 100 to 1000 lx.

Figure 26 presents the correct detections recorded for each illumination intensity level.

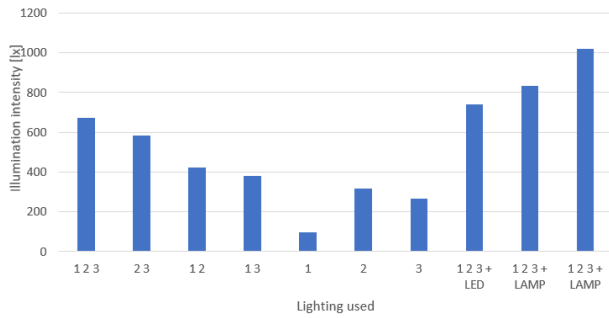


Fig. 25. Illumination intensity levels corresponding to different lighting configurations

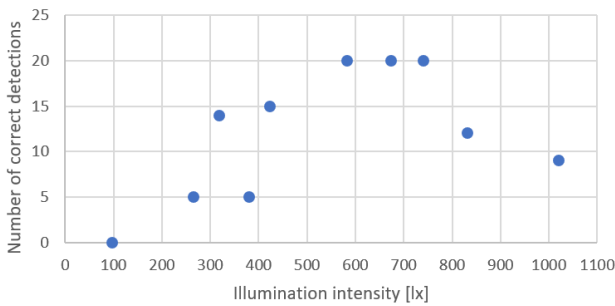


Fig. 26. Number of correctly identified colours under varying illumination intensities

Figure 27 compares the number of correct detections against illumination intensity, differentiated by lighting type and combination (LED, fluorescent lamp). Generally, increased illuminance correlates with improved detection accuracy. However, excessive brightness from multiple concurrent sources can negatively impact recognition precision.

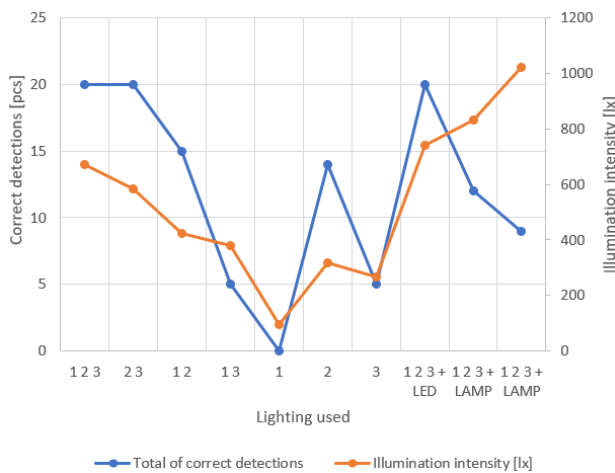


Fig. 27. Detection performance versus illumination under various lighting setups

Figure 28 displays the number of correct detections for each colour (blue, green, red, and yellow) as a function of illumination intensity.

Red demonstrated the highest robustness across various lighting conditions, whereas green, blue, and yellow exhibited reduced reliability. Green showed diminished detection accuracy under low illuminance, indicating higher sensitivity to suboptimal lighting.

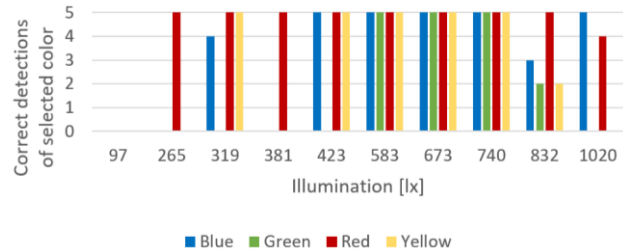


Fig. 28. Correct detections of individual colours as a function of illumination intensity

A key principle should be that lighting conditions remain constant throughout the day and that no shadows are cast on the workspace. Based on the table and the graphs, it can be concluded that the system operates flawlessly when the illumination intensity at the centre of the pallet falls within the range of 580 to 740 lx.

6. CONCLUSION

The obtained results confirmed the critical influence of lighting conditions on the reliability of the collaborative robot's vision system in sorting coloured aluminium pucks. Based on experiments conducted under ten different lighting configurations ranging from 97 lx to 1024 lx, the optimal operational range of the system was identified between 550 and 740 lx, where the robot achieved the highest accuracy and performance stability. Under very low illumination levels (e.g., 97 lx), the iRVision 2D camera system demonstrated significant difficulty correctly identifying colours, resulting in a marked drop in sorting accuracy. Similarly, at the highest tested intensity (1024 lx), system performance degraded, likely due to sensor oversaturation or glare, adversely affecting detection quality.

These findings underscore the importance of maintaining well-defined lighting conditions in vision-based collaborative robotic applications. This necessitates ensuring a stable illumination environment within the optimal range to guarantee reliable system operation. At the same time, the system exhibits limitations under

extremely low and excessively high lighting, which constrains its applicability outside this range.

Future research should thus focus on enhancing the robustness of the vision system against varying illumination. This may involve implementing adaptive image-processing algorithms or deploying more advanced sensors with higher dynamic range. Additionally, the integration of controllable lighting sources directly into the robotic workstation could help ensure consistent illumination even in dynamic environments. Finally, validating system performance under fluctuating lighting and with different types of sorted objects would help confirm the generalizability of the findings and further improve the overall robustness of the proposed solution.

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Evaluarea fiabilității roboților colaborativi pentru sortarea culorilor în condiții variabile de iluminare

Obiectivul acestei cercetări a fost evaluarea fiabilității unui sistem robotic colaborativ pentru sortarea discurilor de aluminiu colorate în condiții variabile de iluminare. Stația experimentală a fost proiectată și implementată pentru a evalua fiabilitatea procesului de sortare. Sistemul utilizează un robot FANUC CR-7iA/L echipat cu o cameră iRVision 2D pentru recunoașterea culorilor, lucrând în cooperare cu senzori inductivi și optici. Un program de control personalizat integrează subrutine pentru detectarea culorilor, manipularea discurilor și controlul benzii transportoare. Rezultatele testelor indică o performanță optimă de recunoaștere în intervalul 550–740 lx din spectrul total de 97–1024 lx. Această soluție oferă automatizare eficientă, un nivel

ridicat de siguranță și o adaptabilitate ușoară la diverse sarcini de producție. Engineering Informatics, vol. 62, p. 102596, Oct. 2024, doi: 10.1016/j.aei.2024.102596.

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