Measuring the Movement Force of a CoBot to Evaluate Hand Guiding Operation

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***Abstract*—In this study, we produced a testing model for evaluating the movement force involved in the hand guidance of a collaborative robot (CoBot). Hand guiding is a new concept in the field of CoBots and is one of the main topics of the International Organization for Standardization's Technical Specifications 15066. The movement force of a four-degrees-of-freedom ceiling-mounted CoBot in a workspace was analyzed in this study. The research proposed a new method to evaluate the hand guiding operation of a CoBot: first, the movement force was measured; second, an image model was produced using these measurements; third, the movement forces for a workspace were analyzed; finally, using these image models, conclusions and recommendations were formulated, detailing the safety requirements of hand guiding operations.**

***Keywords*—hand guiding, collaborative robot (CoBot), ISO/TS 15066**

I. Introduction

After collaborative robots (CoBots) were invented in 1996 by Peshkin and Colgate, users and researchers started using them for automated applications. Automation aims to facilitate collaboration between robots and humans in common robotized workplaces for safety and efficacy [1]. Collaboration between humans and robots working in close proximity in a shared workspace is a stimulating feature of Industry 4.0 [2]. The International Organization for Standardization (ISO) published standards ISO 10218 and ISO/Technical Specifications (TS) 15066 to regulate these operations. Four types of collaborative operation exist [3-5]:

1. Safety-rated monitored stop: a stop that is assured without power removal.
2. Hand guiding: manual control of a robot system.
3. Speed and separation monitoring: control of a robot system's speed on the basis of the separation between the robot and any intrusion.
4. Power and force limiting: control of the speed, torque, and motion of the robot to prevent any impact from causing injuries while operating automatically.

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Movement force is a critical aspect in the safety requirements of ISO/TS 15066. In this study, we focused primarily on type two of collaborative operation, hand guiding. This type of operation increases the efficiency of collaboration between a human and a CoBot [6]. Most CoBots can be taught using hand guiding [7]. However, this close form of collaboration can cause collisions [8]. This study used a ceiling-mounted, four-degrees-of-freedom palletizing robot for experimentation. A palletizer is a machine that offers considerable automation in the workspace. The first mechanized palletizer was designed, built, and installed in 1948 by Lamson Corp., and specific types of palletizers include the row-forming palletizer which was introduced in the early 1950s. In row-forming palletizing applications, loads are arranged in a row-forming area and then moved to an area where layer forming occurs. This process is repeated until a full layer of goods is configured to be placed on a pallet. The in-line palletizer was developed in the 1970s when higher speeds were required for palletizing. This palletizer type utilizes a continuous motion flow divider that guides goods into the desired area on the layer-forming platform.

Palletizing CoBots are a widely applied example of automation. Multi-arm palletizing CoBots are effective and have few restrictions. The palletizing robot in this study has a two-group four-link mechanical arm. The experimental robotic arm was designed and built in-house.

The movement force for hand guiding was measured to identify and remove hazards in the operation space. Movement force is the force required to hand guide a CoBot. This is one of the easiest security indicators to monitor; however, the importance of monitoring movement force of hand guiding has been underappreciated. If a dangerous location in an operation space can be identified, it can be avoided. In this study, the movement force of a palletizing CoBot was investigated through low-speed hand guiding. Then, three-dimensional (3D) model images were produced and danger locations were identified.

The remainder of this paper is organized as follows: the experimental method and setup are described in section II, the results and discussion are presented in

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section III, and the conclusions are discussed in section IV.

II. Experimental Method and Setup

A. *The CoBot's Double-parallelogram Linkage Mechanism*

A robot arm with a double-parallelogram linkage mechanism was used in this study. The palletizer CoBot is shown in Fig. 1.

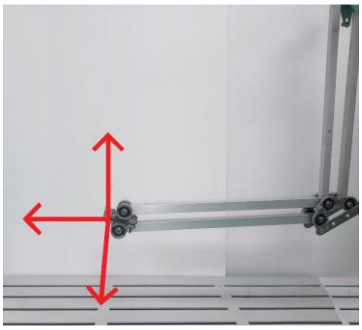


Figure 1. Palletizer collaborative robot for hand guiding.

We addressed collisions, which occur during collaborative operation, from the perspective of movement force. Studies have proposed methods to prevent danger in CoBot operations, including controlling a kinematic model of the robot [9], analyzing the parametrization of control performance and user comfort [10], calculating and tracking trajectories [11], exploring design principles and behavior models [12], and using haptic feedback [13]. We addressed the dangers of CoBot use by monitoring the movement force of hand guiding during collaborative operation.

A simplified robot arm with a double-parallelogram linkage mechanism was used (Fig. 2). The mechanism details are shown in Figs. 2–7. Manually controlled robot systems in accordance with ISO/TS15066 have a robot arm with four binary links, two ternary links, and one quaternary link (Figs. 2–5).

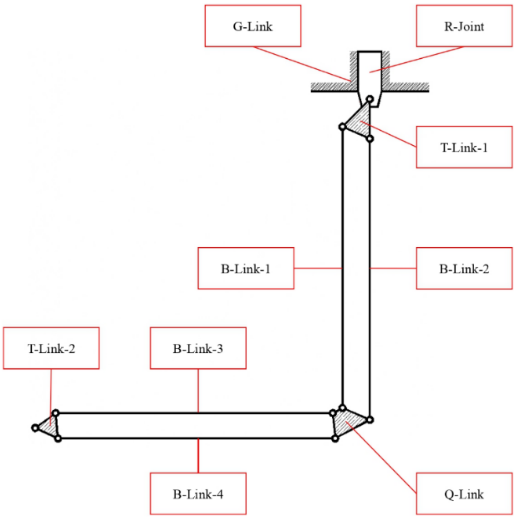


Figure 2. Schematic of the double-parallelogram linkage mechanism in the CoBot arm.

- ***B-Links (Binary Links)***

This CoBot arm has four B-Links: B-Link-1 (355 mm), B-Link-2 (355 mm), B-Link-3 (353 mm), and B-Link-4 (353 mm), shown in Table I.

TABLE I. B-Link Dimensions

Link name	Foul line length
B-Link-1	355 mm
B-Link-2	355 mm
B-Link-3	353 mm
B-Link-4	353 mm

- ***T-Link-1 (Ternary Link)***

T-Link-1 has three edges: L1 (50 mm), L2 (50 mm), and L3 (38 mm), shown in Fig. 3 and Table II.

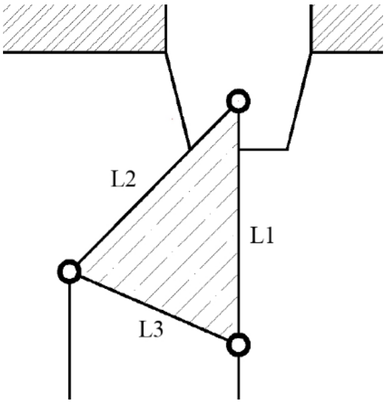


Figure 3. T-Link-1.

TABLE II. T-Link-1 Dimensions

Foul line name	Foul line length
L1	50 mm
L2	50 mm
L3	38 mm

- ***T-Link-2***

T-Link-2 has three edges: L1 (32 mm), L2 (32 mm), and L3 (32 mm), shown in Fig. 4 and Table III.

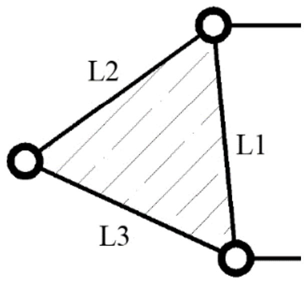


Figure 4. T-Link-2

TABLE III. T-LINK-2 DIMENSIONS

Foul line name	Foul line length
L1	32 mm
L2	32 mm
L3	32 mm

- ***Q-Link (Quaternary Link)***

The Q-Link has four edges. They are L1 (38 mm), L2 (14 mm), L3 (32 mm), and L4 (50 mm), as shown in Fig. 5 and Table IV.

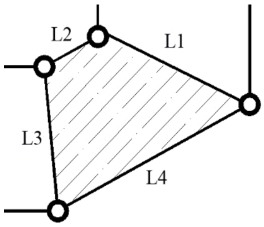


Figure 5. Q-Link.

TABLE IV. Q-LINK DIMENSIONS

Foul line name	Foul line length
L1	38 mm
L2	14 mm
L3	32 mm
L4	50 mm

B. Operating Range

The radius of the CoBot's operating range is 800 mm in two dimensions, and the operating range spans 1.07 m^2 (Fig. 6). The spherical radius is 1 m^3 in three dimensions (Fig. 7).

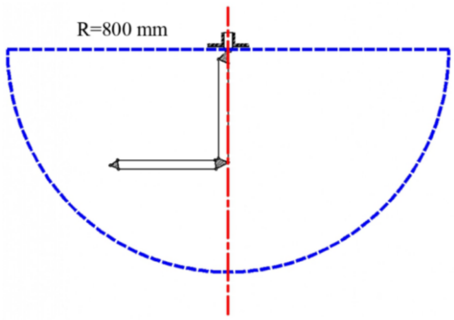


Figure 6. Two-dimensional operating range of CoBot.

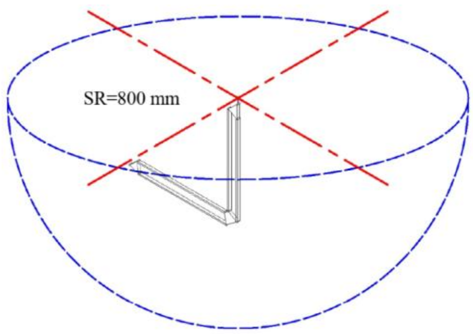


Figure 7. Three-dimensional operating range of CoBot.

C. Sample Range of Experimental Method

The origin position of the sample range was −415 mm on the Z axis and −426 mm on the Y axis (Fig. 8).

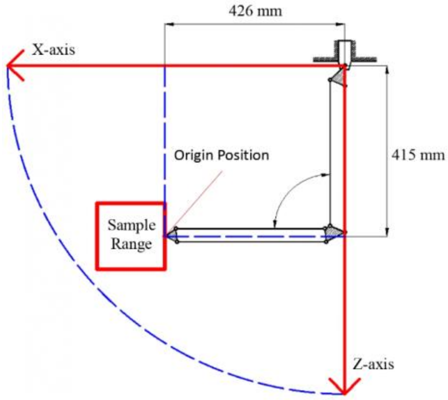


Figure 8. CoBot sample range.

- ***Sample Range***

Our goal following this study is to produce a palletizing CoBot with multidraw functionality in five planes within the working space. The operating space will be divided into five XY planes. These are Z = 80, Z = 40, Z = 0, Z = −40, and Z = −80 mm (Fig. 9). A goal of producing the testing model is to build a 3D model image to identify dangers in the operating space.

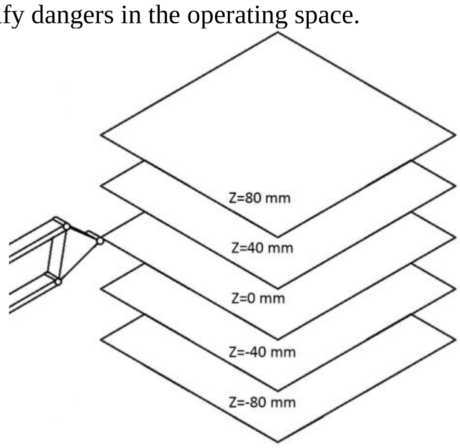


Figure 9. Future goal of a testing model for the full operational range.

The first step was to measure movement force at the sampling points on the Z = 0 mm XY plane (datum plane) and use these results to evaluate the hand guiding operation. A total of 153 (17 × 9) sampling points on the datum plane were used (Fig. 10).

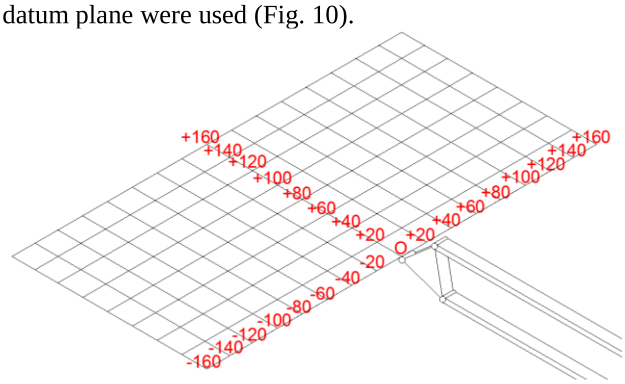


Figure 10. Datum plane for the hand guiding test.

This study primarily involved creating a testing model for evaluation of the movement force of the hand-guiding operation. The movement dimensions of the CoBot were X and Y in the datum plane, making movement force easy to measure using a tension gauge (Fig. 11). The movement of the palletizer was simplified so that it could be easily verified and the hand-guiding operation could be evaluated.

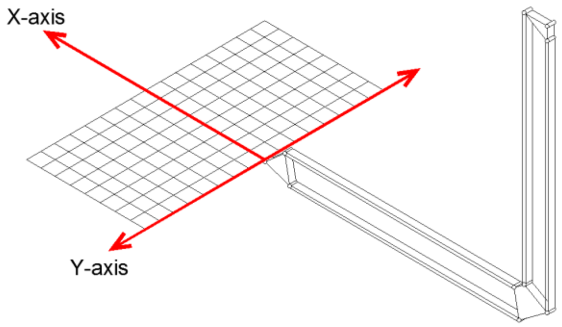


Figure 11. Movement directions of hand guiding in the datum plane.

- ***Measurement Method***

This study used a tension gauge to measure the movement force of the CoBot and to simulate hand-guiding operation (Fig. 12). The gauge has a range of 0–20 N, a resolution of 0.001 N, and deviation of 0.5% (Table V).

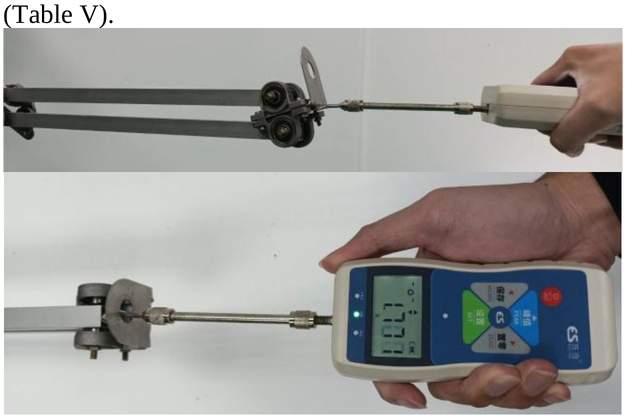


Figure 12. Movement force measurement method.

TABLE V. GAUGE SPECIFICATIONS

Unit	Newton(N)
Range	0~20 N
Resolution	0.001 N
Deviation	0.5%

III. RESULTS AND DISCUSSION

The results from the 153 sampling points in the range (Y ± 160 mm) were divided into 17 graphs by 20 mm intervals for analysis of the movement force and its variation in hand guiding operations (Figs. 13–21).

Y = 0 mm

On the line Y = 0 mm of the datum plane, the movement force was 0–6.8 N and had variation of 0–3.2 N (Fig. 13). Hand guiding is dangerous when the movement force changes (indicated by a bend in the line graph); therefore, careful movement is required to avoid danger at 20–40 and 80–120 mm.

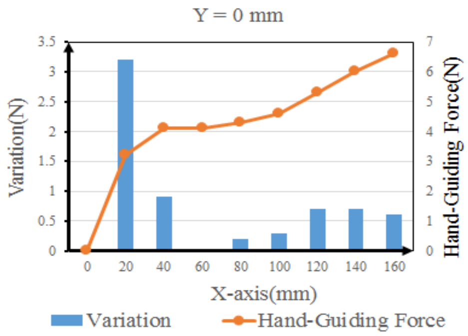


Figure 13. Movement force and its variation along the line Y = 0 mm.

Y = 20 and −20 mm

On the lines Y = 20 and −20 mm of the datum plane, the movement force was 0–6.8 N and had variation of 0–3.1 N (Fig. 14). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 20–60 and 60–80 mm.

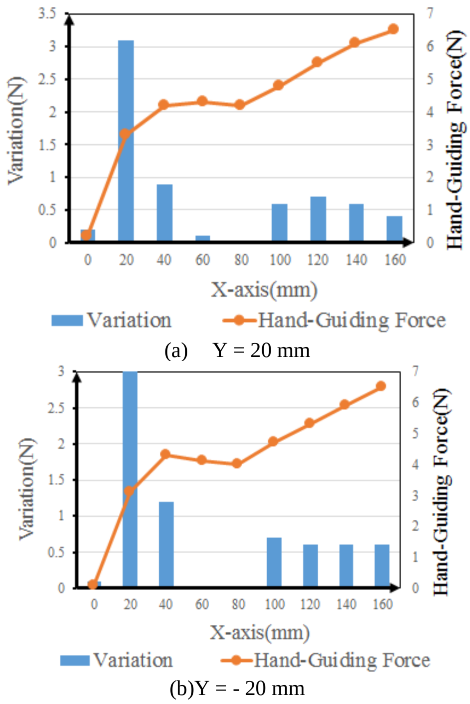
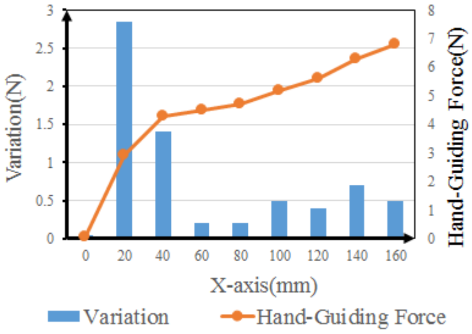


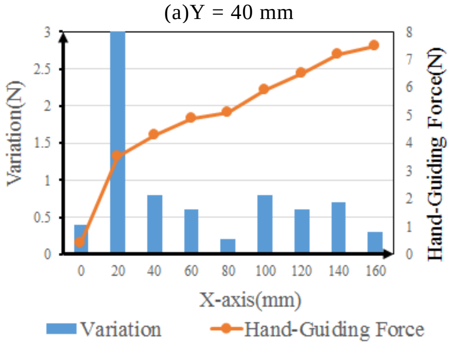
Figure 14. Movement force and its variation along the line (a)Y = 20 mm and (b)Y = − 20 mm.

Y = 40 and −40 mm

On the lines Y = 40 and −40 mm of the datum plane, the movement force was 0–7.6 N and had variation of 0–3 N (Fig. 15). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–60 mm.



(a)Y = 40 mm

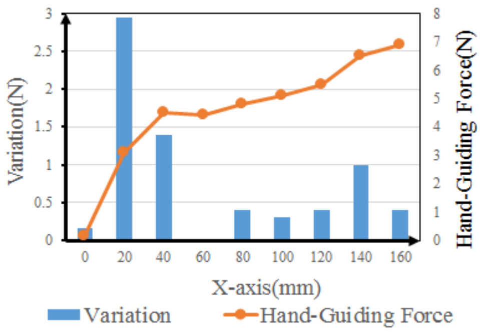


(b)Y = −40 mm

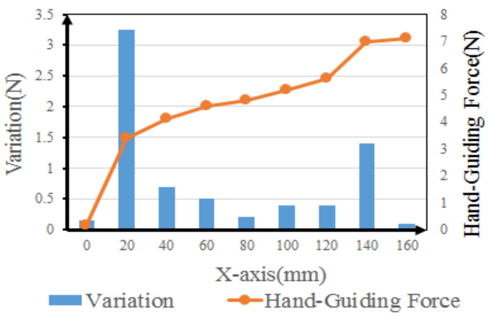
Figure 15. Movement force and its variation along the line (a)Y = 40 mm and (b)Y = −40 mm.

Y = 60 and −60 mm

On the lines Y = 60 and −60 mm of the datum plane, the movement force was 0–7.2 N and had variation of 0–3.3 N (Figs. 16). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–60 and 120–160 mm.



(a)Y = 60 mm

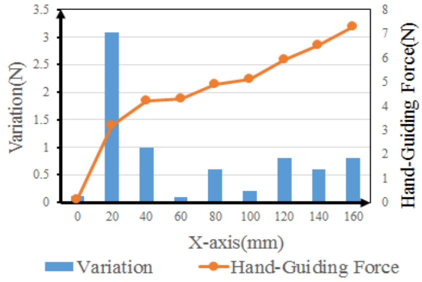


(b)Y = − 60 mm

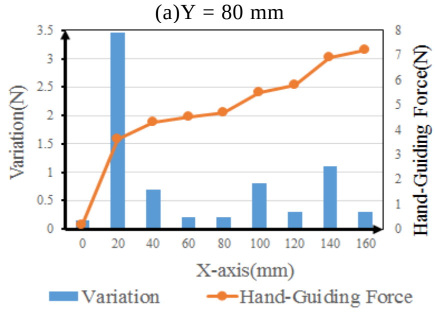
Figure 16. Movement force and its variation along the line (a)Y = 60 mm and (b)Y = −60 mm.

Y = 80 and −80 mm

On the lines Y = 80 and −80 mm of the datum plane, the movement force was 0–7.5 N and had variation of 0–3.5 N (Fig. 17). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–60 mm.



(a)Y = 80 mm

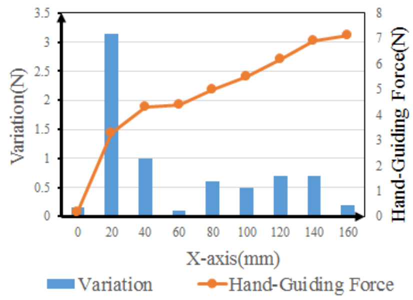


(b)Y = −80 mm

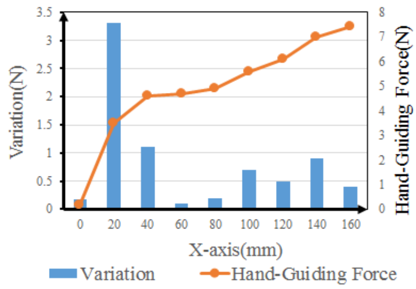
Figure 17. Movement force and its variation along the line (a)Y = 80 mm and (b)Y = −80 mm.

Y = 100 and −100 mm

On the lines Y = 100 and −100 mm of the datum plane, the movement force was 0–7.6 N and had variation of 0–3.4 N (Fig. 18). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 20–60 mm.



(a)Y = 100 mm

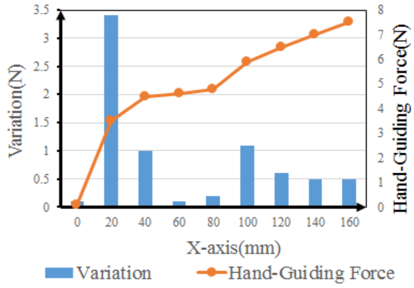


(b)Y = −100 mm

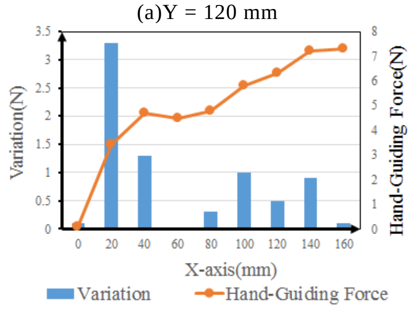
Figure 18. Movement force and its variation along the line (a)Y = 100 mm and (b)Y = − 100 mm.

Y = 120 and –120 mm

On the lines Y = 120 and −60 mm of the datum plane, the movement force was 0–7.8 N and had variation of 0–3.5 N (Fig. 19). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–40 and 60–100 mm.



(a)Y = 120 mm

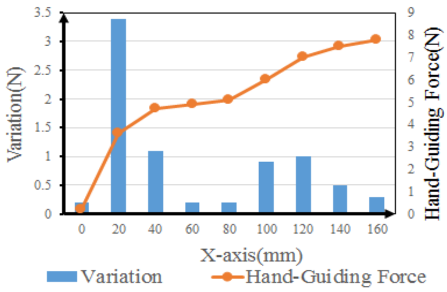


(b)Y = −120 mm

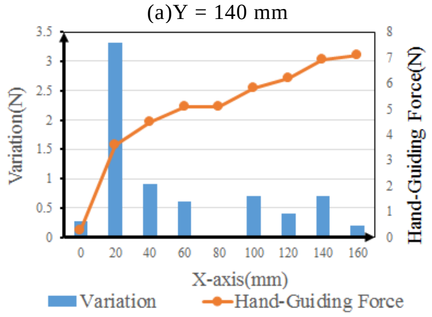
Figure 19. Movement force and its variation along the line (a)Y = 120 mm and (b)Y = −120 mm.

Y = 140 and −140 mm

On the lines Y = 140 and −140 mm of the datum plane, the movement force was 0–8 N and had variation of 0–3.5 N (Fig. 20). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–40 and 60–100 mm.



(a)Y = 140 mm

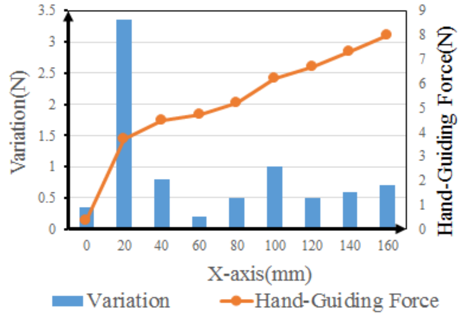


(b)Y = −140 mm

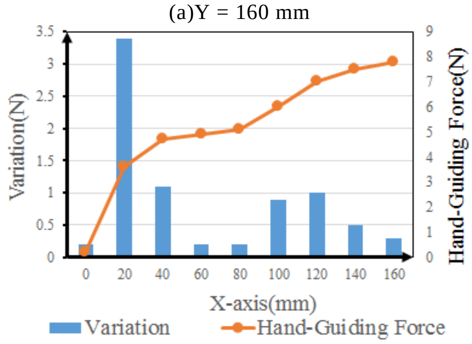
Figure 20. Movement force and its variation along the line (a)Y = 140 mm and (b)Y = −140 mm.

Y = 160 and −160 mm

On the lines Y = 160 and −160 mm of the datum plane, the movement force was 0–8.1 N and had variation of 0–3.5 N (Fig. 21). Positions of danger are indicated by bends in the line graph; careful movement is required for safety at 0–60 and 60–100 mm.



(a)Y = 160 mm



(b)Y = - 160 mm

Figure 21. Movement force and its variation along the line (a)Y = 160 mm and (b)Y = −160 mm.

The results of these 17 graphs were combined in a 3D model image (Figs. 22 and 23), which we used to evaluate our results.

Our results demonstrate the following: if the position of movement is closer to O, the movement force will be smaller. Conversely, if the position of movement is farther from O, the movement force will be greater (Fig. 22). Positions of danger are identified where the 3D model image is not smooth, which also means that the performance of the CoBot in these positions is limited (Fig. 23).

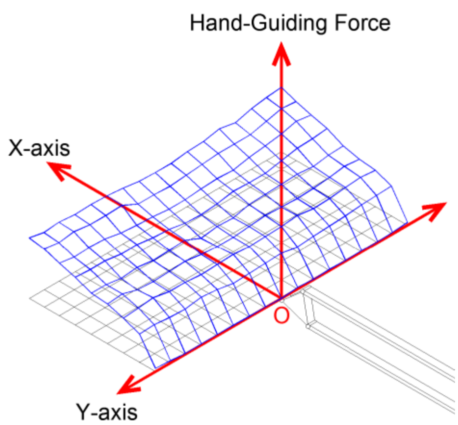


Figure 22. Combined movement force plane.

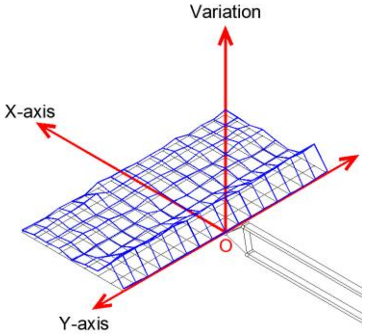


Figure 23. Combined movement force variation plane.

The sampling interval can be adjusted to further evaluate the hand guiding operation. Measurement intervals of 10 mm may sufficiently clarify the model images of the CoBot's movement force variation and facilitate the analysis of the CoBot's performance. If the analysis of a palletizer CoBot gives a smooth movement force variation plane, the CoBot can safely undergo hand guiding.

IV. CONCLUSIONS

This research proposed a testing model for evaluating the movement force of a CoBot's hand guiding operation. In this testing model, the CoBot had a double-parallelogram linkage mechanism that is suited to collaborative operation. A 3D plane showing the variation of the CoBot's movement force was produced and used to evaluate the movement force involved in collaborative operation. The variation in the CoBot's movement force is heavily influenced by its mechanism. Component lengths, joint bearings, and the mass of linkage are the key factors that affect variation. For some CoBot positions, where large variations in movement force exist, require extra attention because the movement force can suddenly increase in these positions. Finally, our goal following this study is to produce a testing model for the full operating space of a palletizer CoBot.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Yun-Ju Chuang and Tsing-Tshih Tsung conducted the design of experimental method and wrote the paper. Yun-Ju Chuang and Yin-Tung Sun performed the data collection and analysis. Yun-Ju Chuang and Ho Chang held the responsibility of revising the manuscript and taking primary responsibility for communication with submission. All authors have approved the final version.

REFERENCES

[1] A. Pauliková, Z. G. Babeľová, and M. Ubárová. "Analysis of the impact of Human–CoBot collaborative manufacturing implementation on the occupational health and safety and the quality requirements." *International Journal of Environmental Research and Public Health*, vol. 18, no. 4, 2021, doi: 10.3390/ijerph18041927.

[2] J. F. Castillo, J. H. Ortiz, M. F. D. Velásquez, and D. F. Saavedra, "COBOTS in industry 4.0: Safe and efficient interaction," *Collaborative and Humanoid Robots*, 2021, doi: 10.5772/intechopen.99540.

[3] ISO 10218-1:2011. Robots and robotic devices–Safety requirements for industrial robots–Part 1: Robots.

[4] ISO 10218-2:2011. Robots and robotic devices–Safety requirements for industrial robots–Part 2: Robot systems and integration.

[5] ISO/TS 15066:2016. Robots and robotic devices–Collaborative robots.

[6] Y. A. Shchenikov, O. S. Gromova, and E. A. Smeshchuk, "The human-CoBot collaboration in mounting and assembly operations in instrument making," *Journal of Physics: Conference Series* 1889, vol. 1889, 2021, doi:10.1088/1742-6596/1889/4/042055.

[7] E. Salvato, W. Vanzella, G. Fenu, and F. A. Pellegrino. "Singularity avoidance for cart-mounted hand-guided collaborative robots: A variational approach," *Robotics*, vol. 11, no. 79, 2022, doi: 10.3390/robotics11040079.

[8] I. Paniti, J. Nacsa, P. Kovacs, and D. Szűr, "Human-robot collision predictor for flexible assembly," *ACTA IMEKO*, vol. 10, no. 3, 2021, doi: 10.21014/acta_imeko.v10i3.1072.

[9] M. Hanses, R. Behrens, and N. Elkmann, "Hand guiding robots along predefined geometric paths under hard joint constraints," in *Proc. 2016 IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*, 2016, pp. 1-5, doi: 10.1109/ETFA.2016.7733600.

[10] F. Müller, J. Jäkel, and J. Suchy, "Tunnel-shaped potential force fields for improved hand guiding of robotic arms," in *Proc. 2015 20th International Conference on Methods and Models in Automation and Robotics (MMAR)*, 2015, pp. 429-434, doi: 10.1109/MMAR.2015.7283914.

[11] S. Moe and I. Schjølberg, "Real-time hand guiding of industrial manipulator in 5 DOF using Microsoft Kinect and accelerometer," in *Proc. 2013 IEEE RO-MAN*, 2013, pp. 644-649, doi: 10.1109/ROMAN.2013.6628421.

[12] M. Bergman, E. de Joode, M. de Geus, and J. Sturm, "Human-CoBot teams: Exploring design principles and behaviour models to facilitate the understanding of non-verbal communication from CoBots," in *Proc. the 3rd International Conference on Computer-Human Interaction Research and Applicationsa* (*CHIRA)*, 2019, pp. 191-198, doi: 10.5220/0008363201910198.

[13] M. Weyrer, M. Brandstötter, and M. L. Husty, "Singularity avoidance control of a non-holonomic mobile manipulator for intuitive hand guidance," *Robotics*, vol. 8, no. 1, 2019, doi: 10.3390/robotics8010014.

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