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Optimal Design and Performance Analysis of a Folding Mechanism Used for a Novel Disinfection Robot

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Abstract. Nowadays, most of the existing disinfection robots cannot operate in areas with limited space. This paper presents the optimal design and performance analysis of a folding mechanism used for a novel medical disinfection robot. This type of robot is adequate for an effective disinfection process because it has small dimensions and can disinfect both hard-to-reach areas and other areas due to its mechanism's structure, which allows a high height variation between the minimum and maximum configuration, also known as the folded and extended position.

Keywords: folding mechanisms, seven-bar linkage, mechanism's performance, disinfection robot design.

1. Introduction

Medical disinfection robots most often use UV-C light to perform air, water and surface sterilization procedures. They are primarily used in the medical field, in hospitals, dental clinics, veterinary clinics and pharmacies, but also in other areas, such as schools, hotels and stadiums [1–2]. UV-C works using a photolytic effect through which the radiation inactivates microorganism so that it can no longer multiply [3]. Nevertheless, when performing the disinfection process it must be considered that each one of the nosocomial pathogens requires a different exposure time to the UV-C light so that it's completely destroyed [4].

Nowadays, more and more medical facilities have implemented disinfection robots, since their overall effectiveness has proven to be better than the standard manual cleaning [5]. However, most of the currently available medical disinfection robots have large dimensions, bulky design and often can operate only in a singular

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configuration [6]. Therefore, considering these mentioned aspects, it is impossible for them to perform an effective disinfection process, by sterilizing also the hard-to-access areas or areas with limited or narrow space available, which are already known to be reservoirs of infection.

Nonetheless, a good solution to this particular problem would be to design and use disinfection robots with folding mechanisms and a mobile platform [7]. The folding mechanism provides different configurations, from the minimum configuration known as the folded position, to the maximum configuration, known as the extended position. The mobile platform ensures navigation through the facility, while also disinfecting the floor, since the bottom of the platform can be cut in order to improve even more the disinfection process.

This paper presents the optimal design and performance analysis of a folding mechanism, specifically the $7\text{-RR}(\text{RRRR})\text{RR}$ seven-bar linkage, further used for the novel design of a medical disinfection robot. This will ensure the most effective disinfection process in the medical facilities, by overcoming the disadvantages of the currently available disinfection robots, mostly by being able to disinfect the hard-to-reach areas, which are already known to be sources of infection.

2. Analysis of the selected folding mechanism – the $7\text{-RR}(\text{RRRR})\text{RR}$ seven-bar linkage

The optimal synthesis of the selected folding mechanism structure, the $7\text{-RR}(\text{RRRR})\text{RR}$ seven-bar linkage, presented in Fig. 1, has already been performed in a previous paper [8].

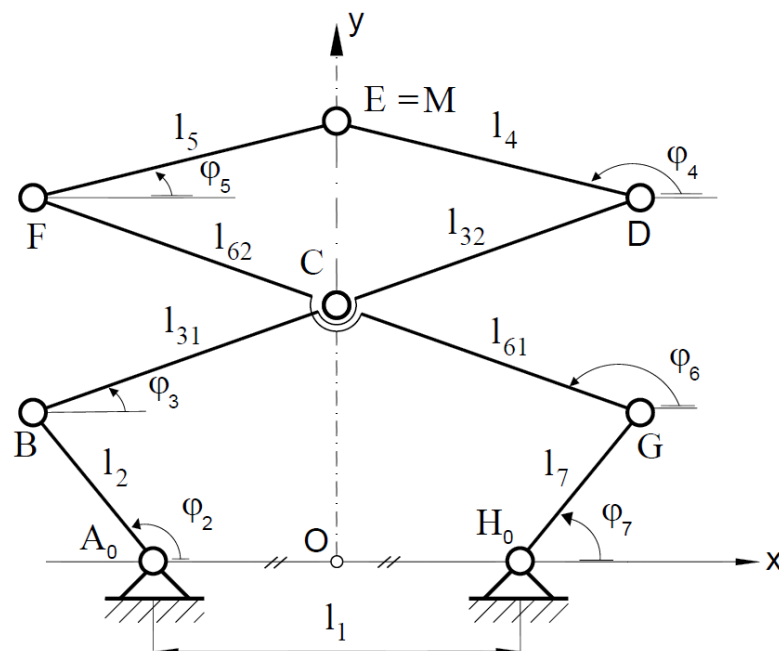


Fig. 1. Kinematic design of the folding mechanism.

The design of the mechanism is symmetrical to the y axis, while the lengths of the driven links l_{31} , l_{32} , l_4 , l_5 , l_{61} , l_{62} , as well as the lengths of the drive elements l_2 and l_7 , were selected to be identical due to functional requirements.

The coordinates of the characteristic point M of the symmetrical 7-RR(RRRR)RR seven-bar linkage can be computed as:

$$x_M = -\frac{l_1}{2} + l_2 \cdot \cos(\varphi_2) + l_{31} \cdot \cos(\varphi_3) + l_{62} \cdot \cos(\varphi_6) + l_5 \cdot \cos(\varphi_5) \quad (1)$$

$$y_M = l_2 \cdot \sin(\varphi_2) + l_{31} \cdot \sin(\varphi_3) + l_{62} \cdot \sin(\varphi_6) + l_5 \cdot \sin(\varphi_5) \quad (2)$$

for the left side of the symmetric mechanism, and:

$$x_M = \frac{l_1}{2} + l_7 \cdot \cos(\varphi_7) + l_{61} \cdot \cos(\varphi_6) + l_{32} \cdot \cos(\varphi_3) + l_4 \cdot \cos(\varphi_4) \quad (3)$$

$$y_M = l_2 \cdot \sin(\varphi_2) + l_{61} \cdot \sin(\varphi_6) + l_{32} \cdot \sin(\varphi_3) + l_4 \cdot \sin(\varphi_4) \quad (4)$$

for the right side of the symmetric mechanism, where:

$$\varphi_6 = \pi - \varphi_3 \quad (5)$$

which leads to:

$$\begin{aligned} \cos(\varphi_6) &= -\cos(\varphi_3) \\ \sin(\varphi_6) &= \sin(\varphi_3) \end{aligned} \quad (6)$$

Furthermore, by separating the terms which contain angle φ_5 in equations (1)–(2) and angle φ_4 in equations (3)–(4), it results the following transmission functions of the seven-bar linkage:

$$\begin{aligned} F_2(y_M, \varphi_2) &= y_M^2 + \frac{l_1^2}{4} + l_2^2 - l_5^2 - l_1 \cdot l_2 \cdot \cos(\varphi_2) - \\ &\quad - 2 \cdot y_M \cdot l_2 \cdot \sin(\varphi_2) - 4 \cdot y_M \cdot l_{31} \cdot \sin(\varphi_3) + \\ &\quad + 4 \cdot l_{31}^2 \cdot \sin(\varphi_3)^2 + 4 \cdot l_2 \cdot l_{31} \cdot \sin(\varphi_2) \cdot \sin(\varphi_3) \end{aligned} \quad (7)$$

$$\begin{aligned} F_7(y_M, \varphi_7) &= y_M^2 + \frac{l_1^2}{4} + l_7^2 - l_4^2 + l_1 \cdot l_7 \cdot \cos(\varphi_7) - \\ &\quad - 2 \cdot y_M \cdot l_7 \cdot \sin(\varphi_7) - 4 \cdot y_M \cdot l_{61} \cdot \sin(\varphi_6) + \\ &\quad + 4 \cdot l_{61}^2 \cdot \sin(\varphi_6)^2 + 4 \cdot l_7 \cdot l_{61} \cdot \sin(\varphi_7) \cdot \sin(\varphi_6) \end{aligned} \quad (8)$$

Nevertheless, the remaining angles φ_3 and φ_6 from equations (7) and (8) can be once again substituted with the following relationships:

$$\varphi_3 = \arccos\left(\frac{\frac{l_1}{2} - l_2 \cdot \cos(\varphi_2)}{l_{31}}\right) \quad (9)$$

$$\varphi_6 = \arccos\left(\frac{\frac{l_1}{2} + l_7 \cdot \cos(\varphi_7)}{-l_{61}}\right) \quad (10)$$

and:

$$x_M = 0 \quad (11)$$

3. Performance analysis of the folding mechanism –7-RR(RRRR)RR seven-bar linkage

The resulting parameters of the analyzed folding mechanism, the 7-RR(RRRR)RR seven-bar linkage, were already computed as a result of an optimized synthesis method and are presented in Table 1.

Fig. 2 presents the seven-bar linkage computed with the parameters' values presented in Table 1, in its two extreme configurations, the folded position (green) and in the extended position (red).

Table 1. Resulting parameters of the seven-bar linkage

Parameter	Value [mm]
l_1	39
l_2, l_7	37
$l_{31}, l_{32}, l_4, l_5, l_{61}, l_{62}$	57.5
y_{min}	30
y_{max}	199
Total length on x direction	76

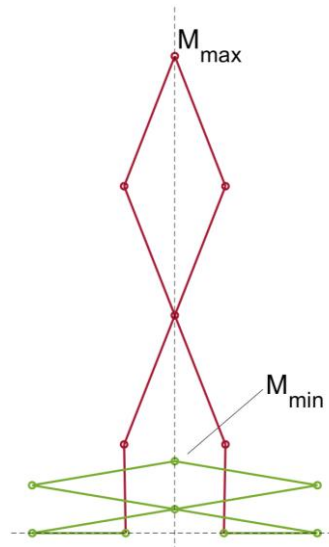


Fig. 2. The analyzed seven-bar linkage in the folded position (green) and in the extended position (red).

In order to perform the performance analysis of the selected folding mechanism, the first step implies determining the Jacobian matrix determinants $\det(J_q)$ and $\det(J_x)$, further expressed with the following equations:

$$\det(J_q) = \begin{vmatrix} \frac{\partial F_2(X,Q)}{\partial \varphi_2} & \frac{\partial F_2(X,Q)}{\partial \varphi_7} \\ \frac{\partial F_7(X,Q)}{\partial \varphi_2} & \frac{\partial F_7(X,Q)}{\partial \varphi_7} \end{vmatrix} = 0 \quad (12)$$

$$\det(J_x) = \begin{vmatrix} \frac{\partial F_2(X,Q)}{\partial x_M} & \frac{\partial F_2(X,Q)}{\partial y_M} \\ \frac{\partial F_7(X,Q)}{\partial x_M} & \frac{\partial F_7(X,Q)}{\partial y_M} \end{vmatrix} = 0 \quad (13)$$

The vector of the input parameters of the folding mechanism is $Q = [\varphi_2 \varphi_7]^T$ while the vector of the output parameters is $X = [x_M y_M]^T$.

Fig. 3 and Fig. 4 illustrate that type I and type II singularities are avoided in the entire workspace, since all values of the Jacobian matrix determinants J_q and J_x are different from the zero value.

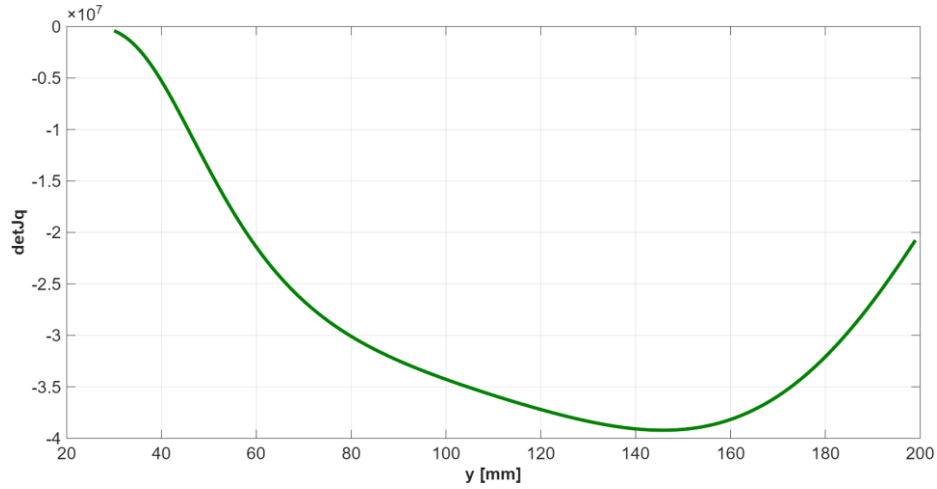


Fig.3. Type I Singularities.

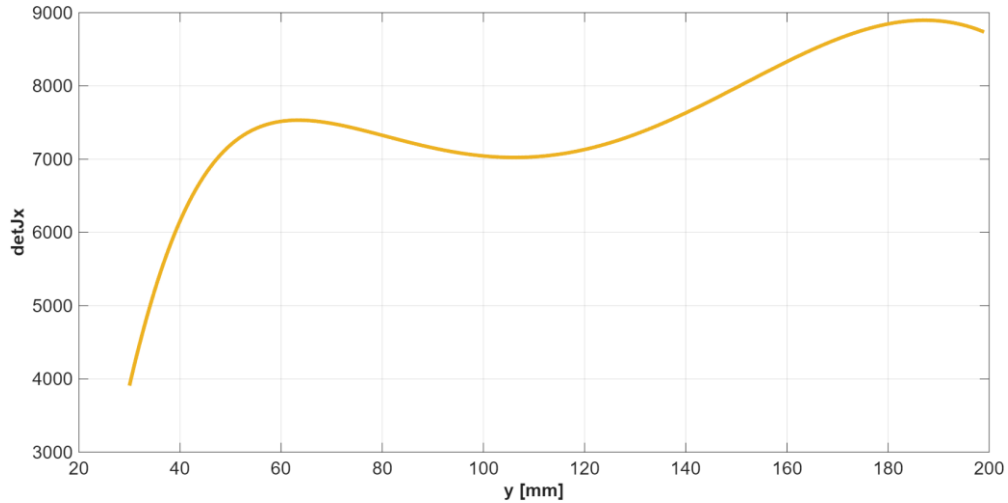


Fig.4. Type II Singularities.

The Local Manipulability Index (LMI) is defined as the absolute value of the Jacobian matrix determinant $\det(J)$ and can be expressed as [9]:

$$LMI = |\det(J)| = |\det(J_x \cdot J_q^{-1})| \quad (14)$$

The normalized values of the Local Manipulability Index are obtained by implementing an algorithm that transposes the initial values to values in the interval of $[0;1]$. The normalized values of the LMI of the folding mechanism structure, the 7-RR(RRRR)RR seven-bar linkage is illustrated in Fig. 5. It can be observed that better manipulability is associated with lower values of the mechanism's height.

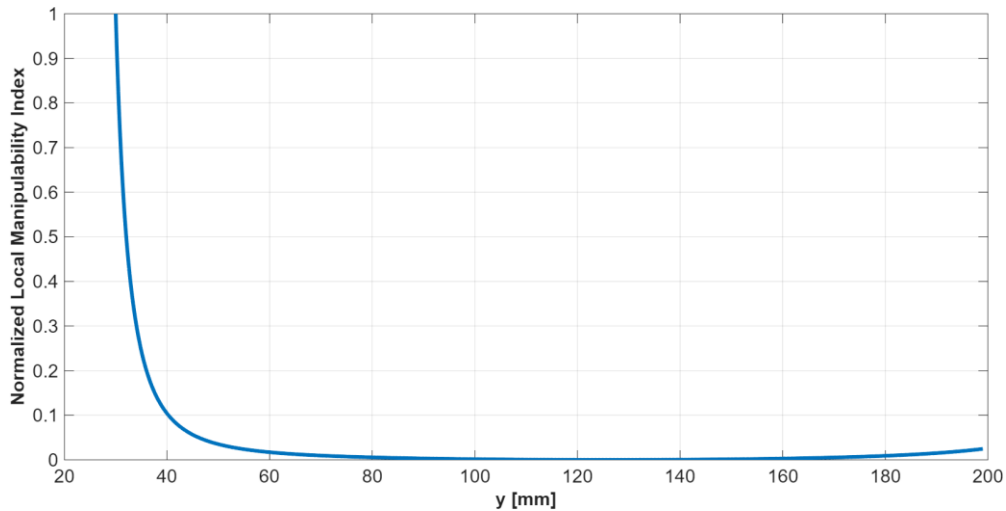


Fig. 5. Normalized Local Manipulability Index (LMI).

Furthermore, the Global Manipulability Index (GMI) can be computed in the entire workspace W of the folding mechanism, by using the following relationships:

$$GMI = \frac{\int_W \frac{1}{LMI} dw}{\int_W dw} \quad (15)$$

The resulting value is further presented in Table 2. Better GMI values are considered to be closer to the ideal value of 1.

Table 2. Global Manipulability Index (GMI)

Index	Value [-]
GMI	0.0284

Next index is the Condition Number (CN), which is expressed as the product between the absolute value of the determinant of the Jacobian matrix J and the absolute value of the determinant of its inverse:

$$CN = \|J\| \cdot \|J^{-1}\| \quad (16)$$

Fig. 6 presents the resulting values of the Condition Number for the analyzed folding mechanism, the symmetrical 7-RR(RRRR)RR seven-bar linkage.

Likewise, an ideal CN's value is considered to be closer to the value of 1, which means that the higher the value of the total height of the mechanism, the lower the value of the Condition Number.

Fig. 7 illustrates the resulting values of the Local Condition Index (LCI), in the same considered workspace. LCI is a kinematic performance measure, which is again

favorable when its values are closer to the value of 1. It can be observed that the best values of the LCI are achieved when the height of the folding mechanism is between 125 mm and 199 mm.

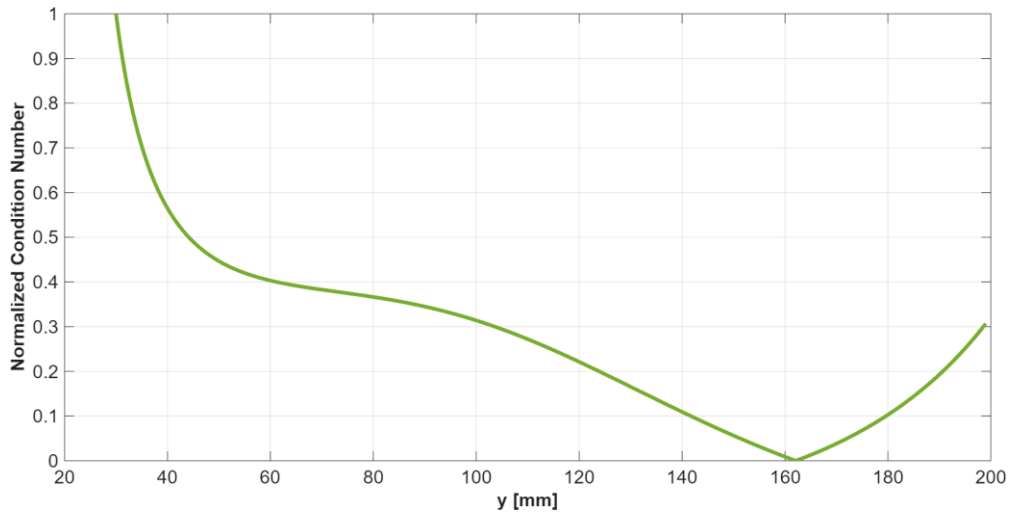


Fig. 6. Normalized Condition Number (CN).

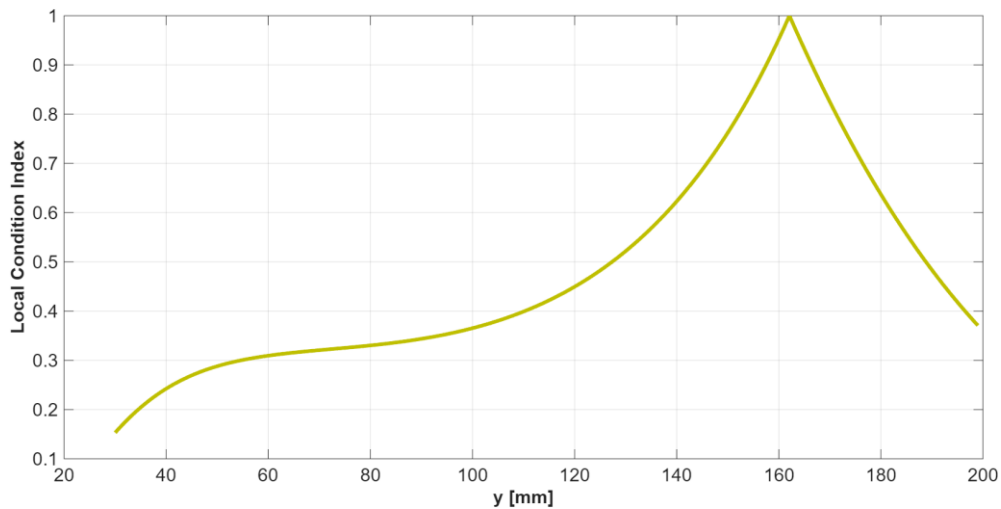


Fig. 7. Local Condition Index (LCI).

Additionally, the Global Conditioning Index (GCI) can be obtained by computing the local condition index (LCI) across the entire workspace W , using the following relationship:

$$GCI = \frac{\int_W \frac{1}{CN} dw}{\int_W dw} \quad (17)$$

The resulting value of the Global Condition Index is presented in Table 3. Similarly, an ideal value of GCI is considered to be the value 1, which means that the result achieved by the analyzed 7-RR(RRRR)RR seven-bar linkage is not very satisfying, since it's not even half of the desired value.

Table 3. Global Condition Index (GCI)

Index	Value [-]
GCI	0.4789

Next index is the Kinematic Condition Index (KCI), which is another indicator of the folding mechanism's performances. It is computed using the inverse of the lowest CN's value:

$$KCI = \frac{1}{CN_{min}} \cdot 100 [\%] \quad (18)$$

Table 4 presents the resulting value of the Kinematic Condition Index. The results are very satisfactory, since the value of KCI is almost 100%, which is considered to be the ideal value.

Table 4. Kinematic Condition Index (KCI)

Index	Value [%]
KCI	99.9536

Fig. 8 presents the resulting values of the Local Stiffness Index (LSI) in the workspace that has been considered. Most favorable values of the LSI are considered to be closer to 1, which means that the best values of the Local Stiffness Index are achieved once again when the folding mechanism's height is between 125 mm and 199 mm.

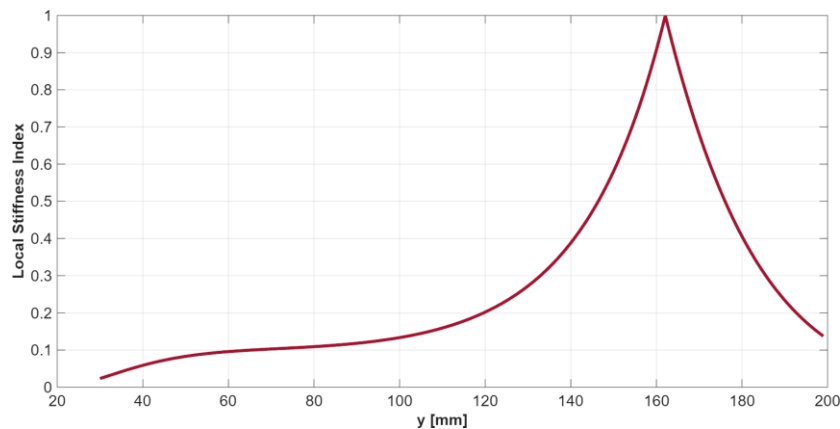


Fig. 8. Local Stiffness Index (LSI)

Moreover, the Global Stiffness Index (GSI) can be obtained by computing the Local Stiffness Index (LSI) across the entire workspace W , using the following relationship:

$$GSI = \frac{\int_w \frac{1}{LSI} dw}{\int_w dw} \quad (19)$$

The results of the Global Stiffness Index (GSI) are illustrated in Table 5. The resulting value of this performance indicator is not very satisfactory, since it's very far from the ideal value of 1.

Table 5. Global Stiffness Index (GSI)

Index	Value [-]
GSI	0.2725

Lastly, to conclude the performance analysis of the folding mechanism, it must be noted that the best results were obtained for the 7-RR(RRRR)RR seven-bar linkage's height between 125 mm and 199 mm, while less satisfactory results were obtained for a mechanism height lower than 100 mm.

4. Novel design of a disinfection robot with folding mechanism

In order to achieve an even higher maximum height of the mechanism, the resulting folding mechanism structure that will be used for the design of the medical disinfection robot will consist of one additional l_3 ($l_{31} + l_{32}$) element and one additional l_6 ($l_{61} + l_{62}$) element, as can be observed in Fig. 9.

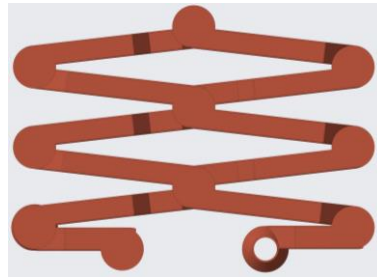


Fig. 9. The resulting folding mechanism structure.

The final design of the medical disinfection robot consists of two identical 7-RR(RRRR)RR seven-bar linkages, that are placed parallel to each other at an established distance (which can be subsequently modified according to different types of requirements). The resulting structure will be located on a mobile platform driven by four mecanum wheels, which ensures the omnidirectional movement of the disinfection robot. Each side part of the platform is cut in the middle, so that it ensures the disinfection of the side areas, when the robot is operating. Moreover, if it is required, the bottom part of the mobile platform can also be cut, in order to permit the sterilization of the floor in the navigation area. Therefore, the disinfection sources, specifically the UV-C light tubes, can be placed both between and on the front of the two seven-bar linkages, which leads to a more effective disinfection process, achieving almost 360° sterilization coverage.

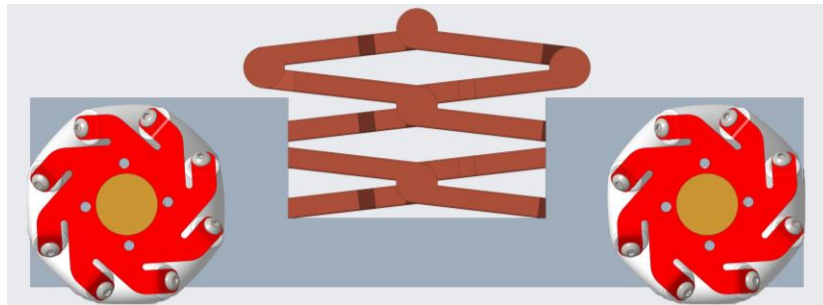


Fig. 10. Medical Disinfection Robot with Folding Mechanism – Folded Position (front).

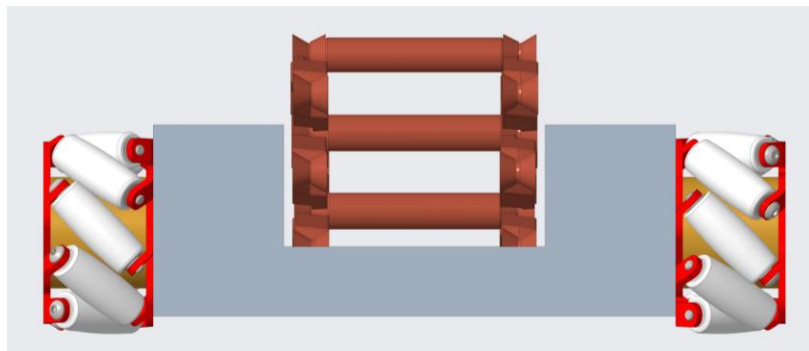


Fig. 11. Medical Disinfection Robot with Folding Mechanism – Folded Position (side).

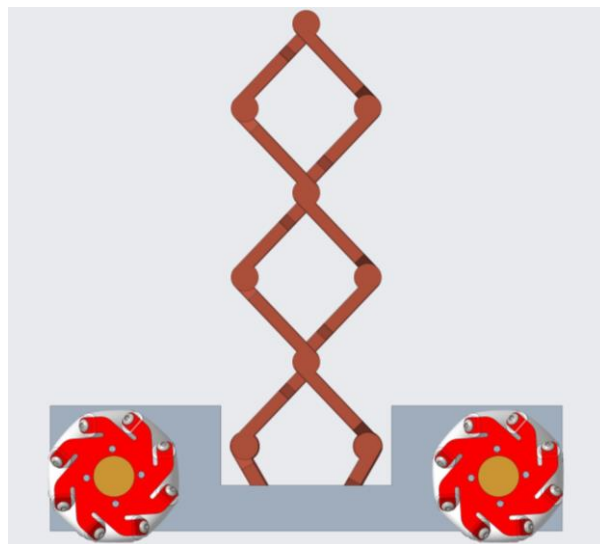


Fig. 12. Medical Disinfection Robot with Folding Mechanism – Extended Position (front).

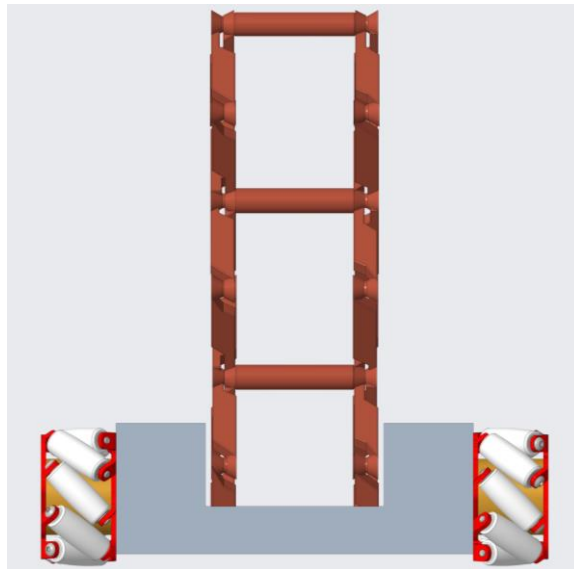


Fig. 13. Medical Disinfection Robot with Folding Mechanism – Extended Position (side).

Fig. 10 and Fig. 11 present the CAD model of the medical disinfection robot in the folded position of the folding mechanism, which is considered as the minimum configuration. This position is adequate for disinfecting the hard-to-reach areas from the medical environment and other facilities, where usually the space is limited and narrow, and the navigation of the classical disinfection robots, which are usually bulky and have large dimensions, is impossible.

Fig. 12 and Fig. 13 present the CAD model of the medical disinfection robot in the extended position of the folding mechanism, which is considered as the maximum configuration. This position is adequate for disinfecting the general areas, where there are no limitations regarding the space of the areas.

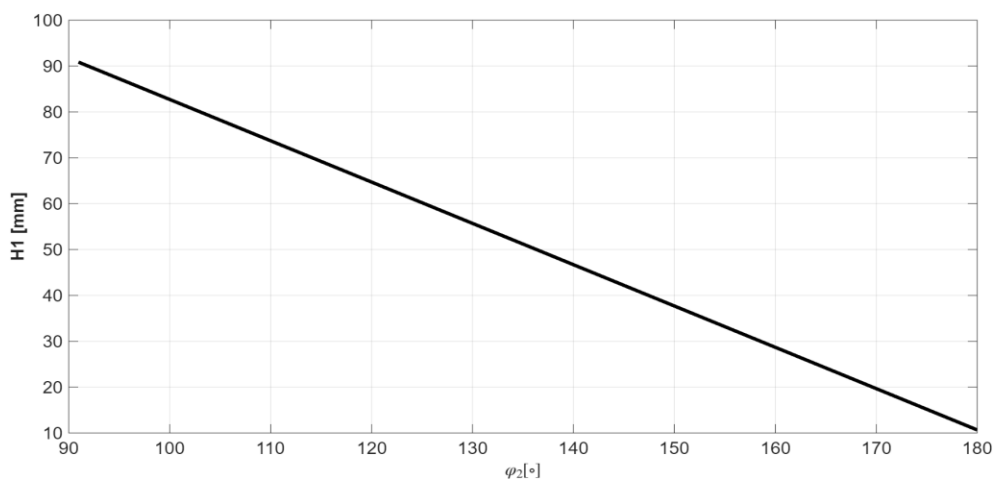


Fig. 14. Height variation of the first loop of the folding mechanism.

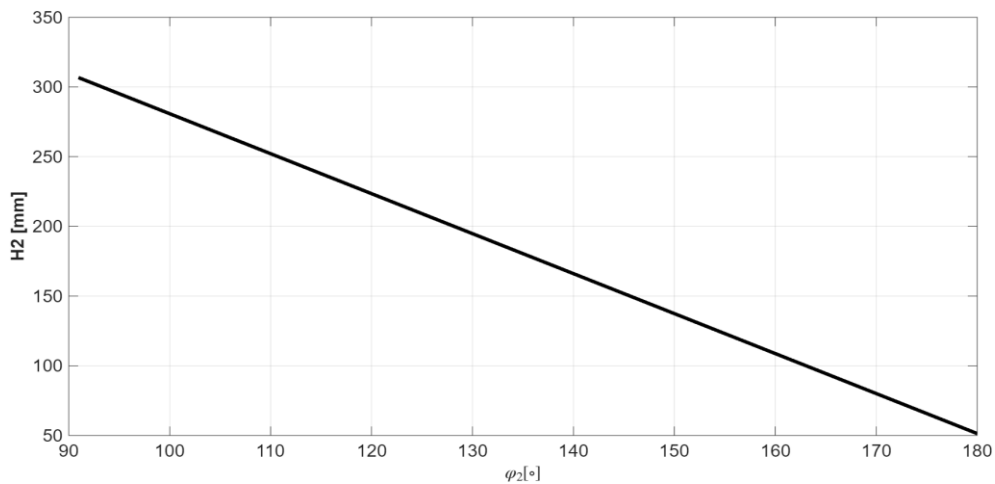


Fig. 15. Height variation of the full folding mechanism.

The simulation of the CAD model shows that the first loop of the folding mechanism increases the theoretical height H_1 of the characteristic point 9 times and for the full mechanism H_2 6 times, as shown in Fig. 14 and Fig. 15.

The simulation of the angular position of the mobile cross elements (up link 3) are presented in Fig. 16 and the corresponding transmission angle between the link 2 and 3, respectively 7 and 6 are presented in Fig. 17.

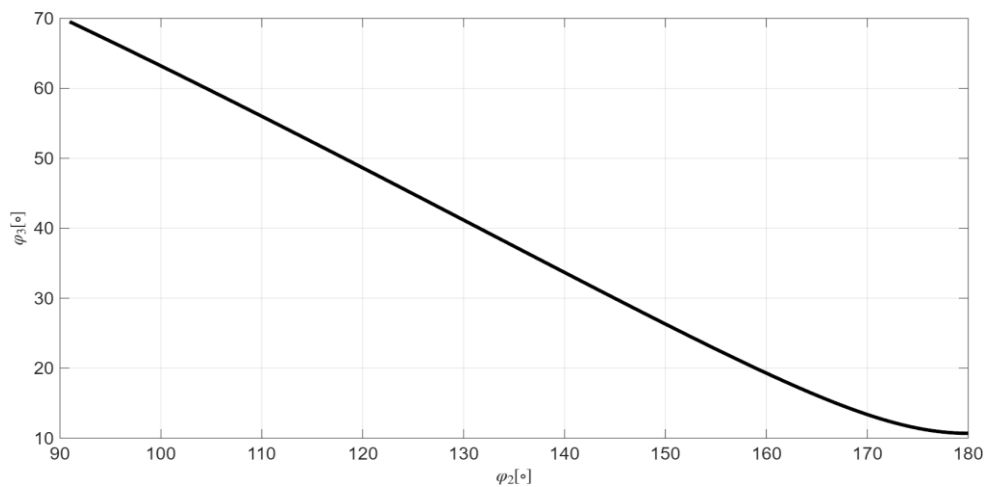


Fig. 16. Positional angle of the mobile cross element of the folding mechanism.

Because on the initial position of the crank (link 2) transmission angle given as:

$$\mu = \pi - \varphi_2 + \varphi_3 \quad (20)$$

is very low $\mu \sim 10^\circ$, it is necessary to limit the transmission angle to minimum $\mu = 30^\circ$, what means the range of the positional angle of the crank should be $[90^\circ, 170^\circ]$. The corresponding heights of the characteristic point have values in the range $H_1 = [20, 90]$ mm for the first loop of the folding mechanism and $H_2 = [70, 310]$ mm.

The height variations $H1$ and $H2$ as well as the positional angle of the mobile cross elements and the transmission angle in regard of the positional angle of the crank are linear.

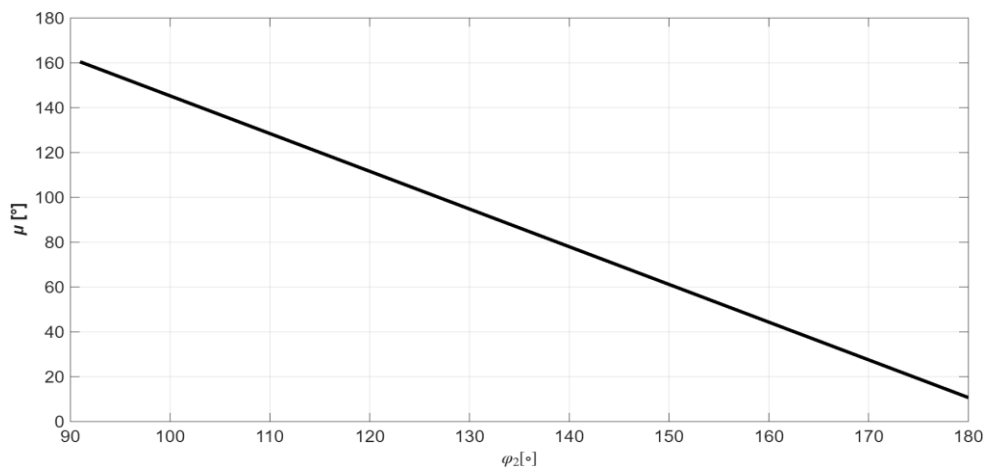


Fig. 17. Transmission angle of the folding mechanism.

5. Conclusions

The paper presented the optimal structure and performance analysis of a folding mechanism further used for the design of a medical disinfection robot. The performance analysis highlighted various important kinematic indicators of a mechanism, such as the manipulability index, condition number, condition index and stiffness index, while some of the results achieved could be indeed further improved. Future works will focus on building the prototype of the disinfection robot with folding mechanism, as well as testing it in different types of scenarios, in order to prove the feasibility of the design.

References

- [1] Kowalski W., *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*, Madison Ave. Springer Science & Business Media, New York, 2010.
- [2] Kesavan J.S., Sagripanti J.-L., *Disinfection of Airborne Organisms by Ultraviolet-C Radiation and Sunlight. Aerosol Science: Technology and Applications*, 2014, p. 417-439.
- [3] Lindblad M., Tano E., Lindahl C., Huss F., *Ultraviolet-C decontamination of a hospital room: Amount of UV light needed*, Burns, **46**, 4, 2020, p. 842-849.
- [4] Kramer A., Schwebke I., Kampf G., *How long do nosocomial pathogens persist on in-animate surfaces? A systematic review*, BMC Infectious Disease, **6**, 2006, p. 130.
- [5] Diab-El Schahawi M., Zingg W., Vos M., Humphreys H., Lopez-Cerero L., Fueszl A., Zahar J.R., Presterl E., *Ultraviolet disinfection robots to improve hospital cleaning: Real promise or just a gimmick?*, Antimicrobial Resistance & Infection Control, **10**, 2021, p. 33.
- [6] Mehta I., Hsueh H.-Y., Taghipour S., Li W., Saeedi S., *UV Disinfection Robots: A Review*, Robotics and Autonomous Systems, 161, 2023.
- [7] Tulcan E.-G., Sticlaru C., Oarcea A. and Lovasz E.-C., *Medical Disinfection Robots: Past vs Future. Improving the Disinfection Process by using Disinfection Robots with Folding Mechanism*, 17th Internat. Conf. on Engineering of Modern Electric Systems (EMES), Oradea, Romania, 2023, p. 1-4.

[8] Tulcan E.-G., Sticlaru C., Oarcea A., Sandu M.-O., Lovasz E.-C., *Optimal Synthesis of a Symmetrical Seven-Bar Linkage's Kinematic Design*, SYROM 2025, **198**, 2026, p. 31-40.

[9] Patel S., Sobh T., *Manipulator Performance Measures - A Comprehensive Literature Survey*, J Intell Robot Syst., **77**, 2025, p. 547–570.