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Vault principle in joining robots

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A major problem with serial kinematic structures, such as serial industrial robots, is their low stiffness. They cannot generally be used for more precise operations, such as CNC milling. One way how to increase their stiffness is to use more mutually connected such robots in the end-effector. In the article [1] it is stated that by connecting two robots it is possible to increase the stiffness of robots about 3.5 times. This is an experimentally determined result, which has not yet been computationally verified nor explained.

For verification, we chose a planar model of a robot, consisting of five flexible arms, interconnected by four flexible joints (Fig. 1). The lower part of the robot is fixed to the base frame. After loading the robot, the end-effector moves in both the horizontal and vertical directions and it also rotates. In the Fig. 2 are two such robots mutually connected. If we model them as springs, then after joining their stiffness should be doubled. Fig. 3 shows

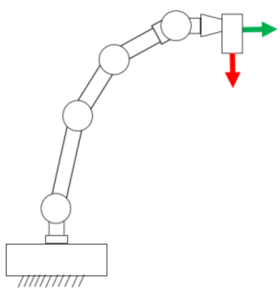

Fig. 1. One robot

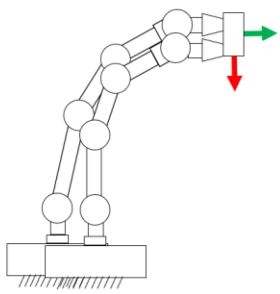

Fig. 2. Two robots

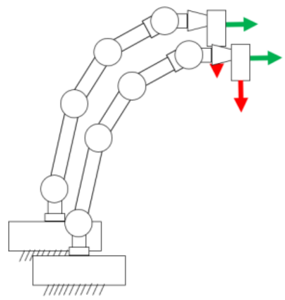

Fig. 3. Two parallel robots

another variant of connecting two robots in a configuration where the corresponding arms are permanently parallel. If we also connect the end-effectors by a rod with joints (Fig. 7), we get a multi-parallelogram, the stiffness of which will depend mainly on the stiffness of the joints. The greatest rigidity will probably be shown by two interconnected symmetrical robots (Fig. 4), in which horizontal, as well as rotational, deformations will be compensated under symmetrical loading. After their connection, the principle of the vault appears (Fig. 5).

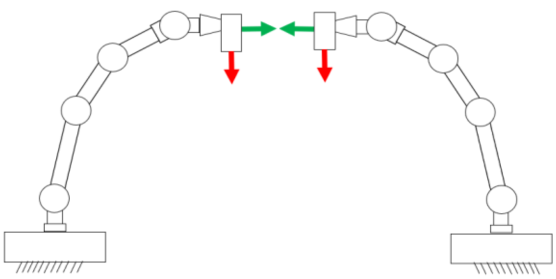

Fig. 4. Two symmetrical robots

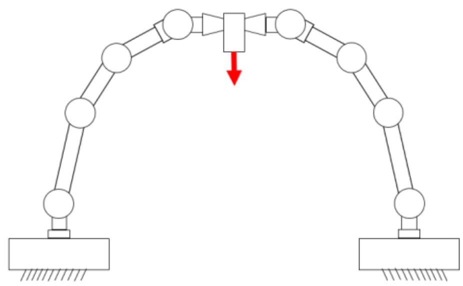

Fig. 5. „Vault“

Calculations were performed by FEM only in one robot(s) position. The arms were modeled by beam elements, the flexible joints were modeled by connecting matrixes, where the only considered flexibility was rotational flexibility.

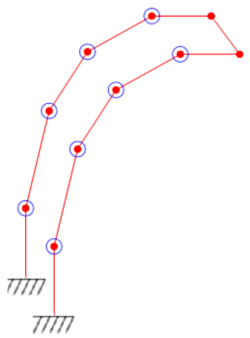

Fig. 6. Parallel – welded end-effectors

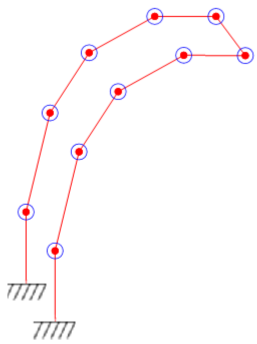

Fig.7. Parallel – joint connection of end-effectors

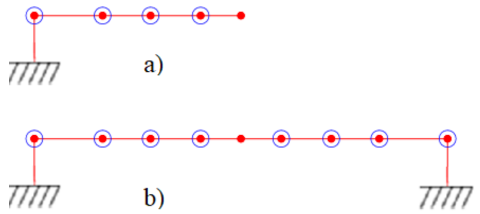

Fig. 8. Horizontal positions

The comparison of the stiffnesses of the individual variants is performed relatively in percentages with respect to the stiffness of one robot (its partial stiffnesses each represent 100 percent). During the verification of the "vault", a significant increase of stiffness was confirmed and further that, in contrast to the classic concave vault in the construction industry, the convex "vault" also works here and gives the same stiffness. For comparison, the horizontal positions of one and two connected robots were also investigated. The result of the comparison is in Table 1. Finally, we verified our assumption that the effect of the vault will be even more pronounced for more flexible joints.

Table 1. Comparison of stiffness at the effector location (due to the stiffness of one robot)

Kinematic scheme according to Stiffness	Fig. 1	Fig. 2	Fig. 6	Fig. 7	Fig. 5	Fig. 8a	Fig. 8b
Horizontal [%]	100	243	246	205	1092	51279	104220
Vertical [%]	100	301	472	339	8337	51	475
Rotational [%]	100	266	492	289	1608	100	914

The work showed that the connection of two robots can significantly increase the resulting rigidity. The highest effect is achieved using the vault principle. It will probably not be possible to use this in the whole workspace, but it will be possible to identify suitable areas, for example for machining. Research could continue by acquiring stiffness maps or extended ideas into space.

Acknowledgements

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References

[1] Valášek, M., Nečas, M., Mráz, L., Increase of stiffness in physically cooperating robots, Proceedings of the 8th ECCOMAS Thematic Conference on Multibody dynamics, Prague, Czech Republic, CTU Publisher, 2017, pp. 577-585.