POLITECNICO DI TORINO
Repository ISTITUZIONALE

About the importance of revolute joints realization in force-sensitive drive interfaces for mobile robots and wheelchairs

Original
About the importance of revolute joints realization in force-sensitive drive interfaces for mobile robots and wheelchairs / Tagliavini, L., Botta, A., Baglieri, L., Colucci, G., Duretto, S., Toccaceli, L., Amodio, F., Quaglia, G.. - ELETTRONICO. - 8:(2025), pp. 90-96. (The 8th Jc-IFToMM International Symposium (in conjunction with The 31st Jc-IFToMM Symposium on Theory of Machines and Mechanisms) Nagano (JP) June 21, 2025 - June 22, 2025) [10.57272/jciftomm.8.0_90].

Availability:
This version is available at: 11583/3007087 since: 2026-01-29T08:21:02Z

Publisher:
Japanese Council of IFToMM

Published
DOI:10.57272/jciftomm.8.0_90

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

02 November 2026

Proceedings of the 8th Jc-IFToMM International Symposium (2025)
The 31st Jc-IFToMM Symposium on Theory of Machines and Mechanisms
21-22 June 2025

About the importance of revolute joints realization in force-sensitive drive interfaces for mobile robots and wheelchairs

Luigi Tagliavini, Andrea Botta, Lorenzo Baglieri, Giovanni Colucci, Simone Duretto, Lorenzo Toccaceli, Francesco Amodio, Giuseppe Quaglia
Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy,
luigi.tagliavini@polito.it

Abstract
This paper presents SensHB.Q, a cost-effective force-torque sensitive interface designed to control omnidirectional motorized systems such as mobile robots, industrial trolleys, and electric-powered wheelchairs. Force-torque-sensitive interfaces are considered more intuitive to use with respect to joysticks since they mimic the way we interact with objects. The main characteristic of SensHB.Q is the fact that measures three components of the applied wrench using only uniaxial load cells, avoiding the adoption of expensive multi-axis force-torque sensors. This work focuses on the executive design of this interface to understand the improvements that can be achieved by using flexure hinges instead of conventional revolute joints in terms of measurement accuracy.

Keywords: Drive Interface, Force-Sensitive System, Omnidirectional Robots, Electric Powered Wheelchairs.

1. Introduction

Over the past decades, many motorized systems for transporting goods and people have been developed from laboratory prototypes to commercial products. Some of the most important applications include industrial transportation, hospital equipment management, indoor and outdoor wheelchairs for people with motor impairments, and precision agriculture. These systems are designed to help people perform tasks that would otherwise be physically demanding or even impossible. Autonomous navigation is becoming increasingly reliable and widespread [1], [2]. However, manual driving still plays an important role in many applications. To enable manual driving of motorized systems, appropriate driving interfaces are essential.

Joysticks are the most widely used interfaces for controlling motorized mobile systems [3], [4], [5], [6]. However, there are some cases where it can be difficult to control a system with a joystick. Consider the following situation: a driver controls a motorized system with a joystick mounted on it; the driver is not above the mobile system; thus, the joystick base is not attached to the driver. In this situation, it is very difficult to maintain a precise tilt angle of the joystick lever, and as a result, it is difficult to precisely control the motion of the motorized system.

To solve this problem, force sensitive interfaces have been proposed in the literature. These interfaces measure the forces and torques applied by the driver to a sensitive area of the device. This information is used to control the motion of the motorized system. For example, Trujillo et al. [7] and Alwan et al. [8] investigated the usage of sensorized handles for controlling electric powered wheelchairs. Also, patent literature analysis reveals similar technologies applied to hospital beds [9]


© 2025 The Authors. This is an open access article under the terms of the Creative Commons Attribution License. (https://creativecommons.org/licenses/by/4.0/)

and industrial robotic arms [10]. Existing force-sensing interfaces are designed for low-mobility systems with up to two degrees of freedom, such as wheelchairs or differential-driven robots, or for high-mobility systems with up to six degrees of freedom. The former class of devices typically uses two single-axis load cells, while the latter class uses six-axis force-torque sensors. The main drawback of the former class of devices is that they cannot be used to control motion with more than two degrees of freedom, while the main drawback of the latter class is the high cost associated with six-axis load cells.

In this context, the authors have already presented the first prototype of SensHB.Q [11], a low-cost force-torque sensitive drive interface intended for omnidirectional motorized systems, such as omnidirectional robots and wheelchairs. This paper briefly describes the concept and functional design of the SensHB.Q, and then analyzes the importance of the executive design of revolute joints by comparing two versions of the device, one with conventional revolute joints and the other with flexure hinges. The two versions are tested to understand the improvements that can be achieved by using flexure hinges instead of conventional revolute joints in terms of measurement accuracy.

2. SensHB.Q concept and functional design

The concept of this force-sensitive interface is illustrated in in Fig. 1 (a). The driver applies small forces and torques to the device, which are measured and converted into commands for the electric-powered mobile system. The main design requirements for SensHB.Q include intuitiveness, affordability, the ability to generate at least three reference signals for controlling omnidirectional planar motions, and the capability to filter out unintended inputs caused by accidental impacts.

To ensure intuitiveness, force-torque inputs are utilized to mimic the natural way humans manipulate objects—by applying forces and torques in alignment with the desired motion. To measure the forces and torques exerted by the driver while maintaining low cost, the device employs single-axis load cells, eliminating the need for expensive six-axis force-torque sensors. SensHB.Q is built around a six-bar mechanism, which is constrained by three uniaxial load cells, as illustrated in Fig. 1 (b). In this way, the load cells are properly loaded on their measurement axis, and it is possible to measure three components of the wrench applied by the driver. In particular, SensHB.Q

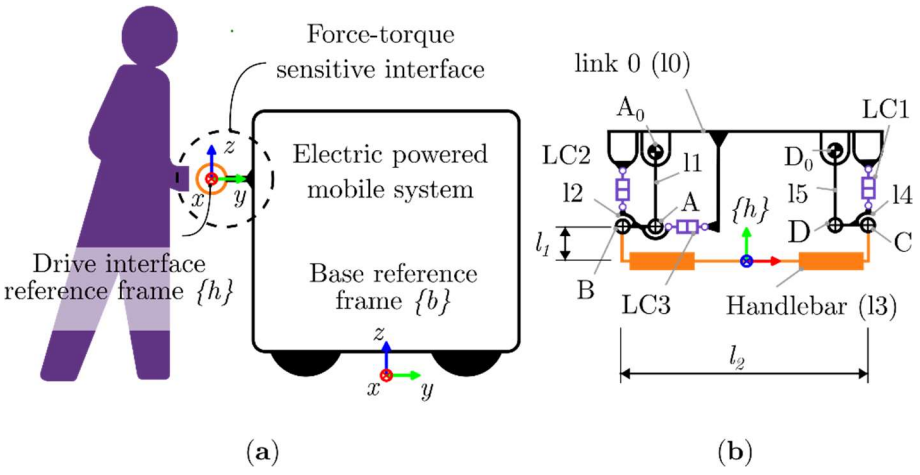


Fig. 1 (a) Concept of force-torque sensitive interfaces; (b) SensHB.Q functional design.

measures the forces on the XY plane of reference frame $\{h\}$ and the torque around the Z axis. These wrench components are used to generate the reference velocity twist for the motorized system.

The isostatic structure, composed of the six-bar linkage and the three uniaxial load cells, is in a specific configuration to limit the influence of assembly inaccuracies on the wrench components measurement. In fact, forces applied along Y axis of $\{h\}$ are measured only by load cells 1 and 2 ($LC1$ and $LC2$), while forces applied along X axis are measured only by load cell 3 ($LC3$).

If we consider the six-bar mechanism without the uniaxial load cells, the handlebar (link 3 in Fig. 1 (b)) has three degrees of freedom, i.e., it can freely move in the plane XY of $\{h\}$. Given the isostatic constraint of the uniaxial load cells and the configuration of the six-bar mechanism, the static equilibrium of the structure can be solved to evaluate the relationship between the applied wrench components and the load cells measurements. In particular, if F_{LCi} is the load cell i measurement (positive when the load cell is under traction), the applied wrench components can be written with respect to $\{h\}$ as in Eq. (1).

$$\begin{bmatrix} M_z \\ F_x \\ F_y \end{bmatrix} = - \begin{bmatrix} -\frac{l_2}{2} & \frac{l_2}{2} & -l_1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} F_{LC1} \\ F_{LC2} \\ F_{LC3} \end{bmatrix} \tag{1}$$

Regarding safety, the device needs to filter out inputs coming from accidental impacts with the handlebar. For this reason, SenseHB.Q has eight capacitive sensors integrated into the ergonomic grips beneath the fingers of the driver. These sensors act as dead-man switches, thus only when the driver is holding the handlebar correctly, the handlebar is activated, and the force-torque inputs are converted into velocity references.

3. SensHB.Q executive design

This section presents two versions of the executive design of SensHB.Q, the first adopts conventional revolute joints, while the second one uses spring steel flexible bands to obtain flexure hinges. These two types of revolute joints design are shown in Fig. 2. Conventional revolute joints are made of three basic components: parts A and B to be joined and the revolute pin. Usually, the tolerances of the holes are such that the pin is fixed to one of the parts and it is free to rotate with respect to the other. Finally, axial constraints are used to secure the pin in the direction of the pin axis. On the contrary, flexure hinges exploit the flexibility of one or more of its components to

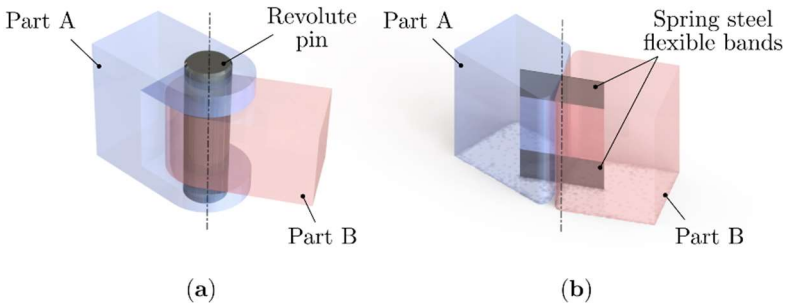


Fig. 2 (a) Conventional revolute joint design; (b) flexure hinges realized using spring steel flexible bands glued into the jointed parts.

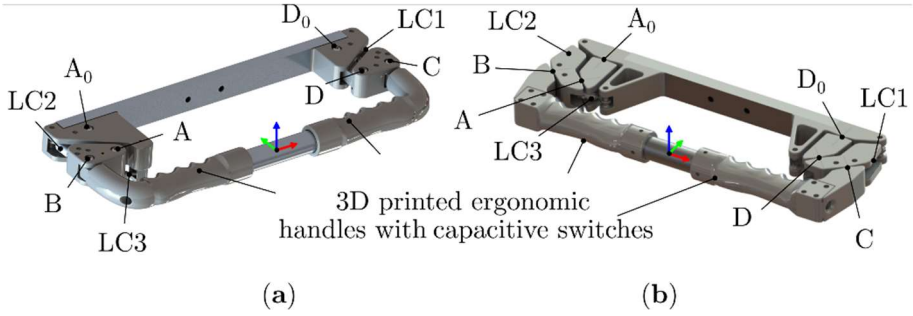


Fig. 3 Executive design of SensHB.Q in two version: (a) with conventional revolute joints; (b) with flexure hinges.

achieve the relative rotation between the two parts to be joined. Flexure hinges can be designed in many ways and made of different materials.

To keep the costs low, the force-sensitive handlebar is designed to be mostly 3D printed with the addition of some commercial components such as aluminum profiles, screw, and nuts. The conventional revolute joints are realized using plastic flange bearings and stainless-steel pins, while flexure hinges are obtained using spring steel flexible bands glued into the 3D printed parts. The executive design of the two version of the device is presented in Fig. 3. The adopted load cells, model FLAE-100N, and amplifier, model LC3A(0-2.5-5V)-24V, are produced and calibrated by Forsentek Co. The load range that can be measured is ± 100 N and the static gain is 0.050 V/N considering also the amplifier.

4. Experimental tests

To evaluate the accuracy of the two versions of SensHB.Q, experimental tests are performed in the laboratories of Politecnico di Torino. Fig. 4 shows the experimental setup. During the tests, a user applies forces and torques to the handlebar and then the measurements of the two versions are compared to the measurements of a commercial six-axis force-torque sensor, SensOne by Bota Systems.

For each version of the interface, ten tests are recorded. The tests relative to the version with conventional revolute joints are numbered from 1.1 to 1.10, while the tests relative to the other version are numbered from 2.1 to 2.10. Fig. 5 shows the results of test 1.9 (Fig. 5 (a)) and test 2.9 (Fig. 5 (b)). The wrench components are expressed with respect to reference frame $\{LC_{6A}\}$. The blue lines represent the commercial sensor measurements, while the orange lines represent the measurements of SensHB.Q. Comparing the measurements of Fig. 5 (a) and Fig. 5 (b), it looks like the version with conventional revolute joints has a larger deviation from the commercial sensor with respect to the version with flexure hinges due to the friction inside the revolute joints.

To better quantify this difference, Table 1 and Table 2 reports the RMS error (root-mean square error) for each test between the measurements of SensHB.Q and SensOne by Bota Systems. The average RMS error for the forces along the X axis are 5.66 N for the version with conventional revolute joints, and 2.34 N for the version with flexure hinges. Regarding the forces along the Y axis, the average RMS errors are respectively 2.00 N and 0.85 N, while regarding the torque around the Z axis the average RMS errors are respectively 0.43 Nm and 0.14 Nm. Thus, the percentage improvements with flexure hinges over conventional revolute joints are 58.6% for F_x, 57.5% for F_y and 67.44% for M_z. This represents a significant improvement in measurement accuracy.

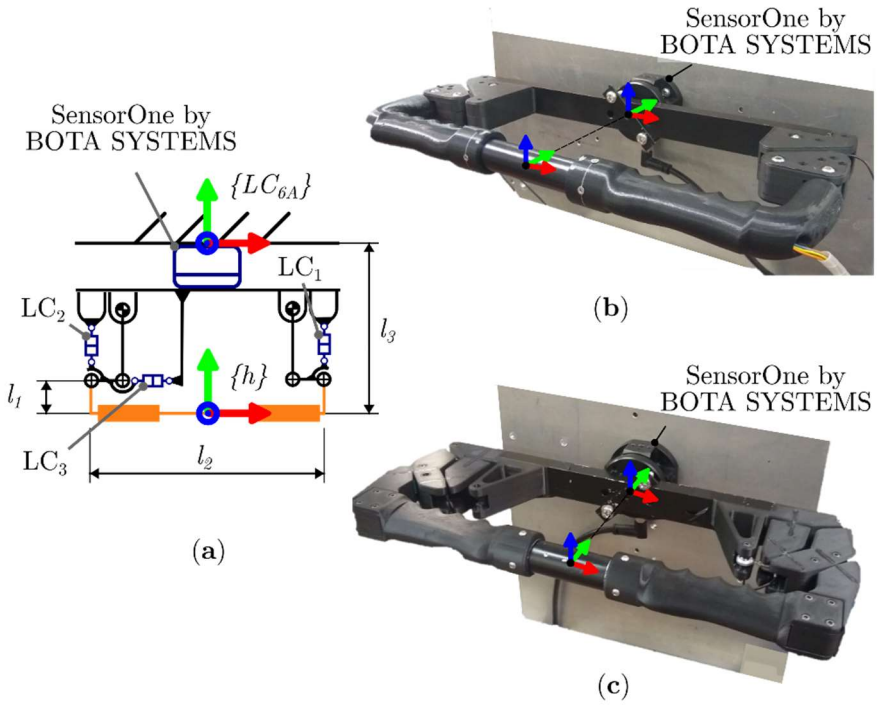


Fig. 4 (a) Functional scheme; (b) version with conventional revolute joints, (c) version with flexure hinges.

Table 1 Root-mean-square errors of the wrench components F_x, F_y and M_z wrt $\{LC_{6A}\}$ between the force/torque measurements of the sensorized handlebar with conventional revolute joints and the six-axis force sensor SensONE.

Test n°	RMS_{F_x} (N)	RMS_{F_y} (N)	RMS_{M_z} (Nm)	Test n°	RMS_{F_x} (N)	RMS_{F_y} (N)	RMS_{M_z} (Nm)
1.1	5.98	2.09	0.39	1.6	4.99	1.46	0.36
1.2	5.75	2.00	0.38	1.7	6.28	2.49	0.52
1.3	5.88	2.10	0.40	1.8	5.90	1.62	0.51
1.4	4.28	1.96	0.36	1.9	6.78	2.00	0.63
1.5	4.68	1.47	0.31	1.10	6.09	2.77	0.45

Table 2 Root-mean-square errors of the wrench components F_x, F_y and M_z wrt $\{LC_{6A}\}$ between the force/torque measurements of the sensorized handlebar with flexure hinges and the six-axis force sensor SensONE.

Test n°	RMS_{F_x} (N)	RMS_{F_y} (N)	RMS_{M_z} (Nm)	Test n°	RMS_{F_x} (N)	RMS_{F_y} (N)	RMS_{M_z} (Nm)
2.1	2.24	0.75	0.13	2.5	2.33	0.73	0.14
2.2	2.46	0.83	0.14	2.6	2.06	0.80	0.13
2.3	2.21	0.82	0.15	2.8	2.66	1.08	0.17
2.4	2.93	1.10	0.16	2.9	1.87	0.69	0.12
2.5	2.72	1.02	0.16	2.10	1.91	0.68	0.12

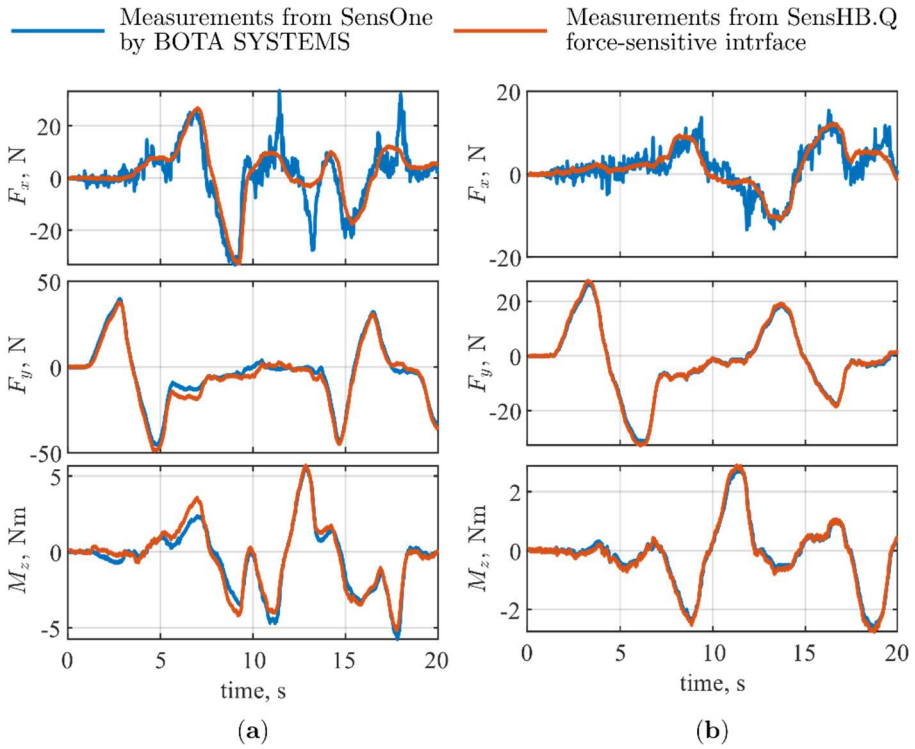


Fig. 5 Measured wrench components with conventional revolute joints (a) (test n°1.9), and with flexure hinges (b) (test n° 2.9). The wrench components are reported in the $\{LC_{6A}\}$ reference frame.

As a final remark, it should be noted that, while evaluating these results, it is important to consider the final goal of this device, i.e., to measure the intention of the driver. Therefore, small measuring errors are acceptable since the device is not intended for precise force-torque measurements.

5. Conclusion

This paper presented the force-sensitive interface SensHB.Q, a cost-effective drive interface for the control of motorized systems such as omnidirectional robots, industrial trolley, and electric powered wheelchairs. SensHB.Q is composed of an isostatic structure based on a six-bar mechanism constrained by three single axis load cells. In this way, three components of the wrench applied by the user to the interface can be measured. This study focused on the importance of revolute joint executive design on the force-torque measurement accuracy. Two versions of the interface had been developed and tested in comparison with a commercial six-axis force-torque sensor, the SensOne by Bota Systems. The results showed that the version with conventional revolute joints is characterized by larger deviation from the commercial sensor measurements with respect to the version with flexure hinges. By computing the average RMS error between the measurements of SensHB.Q and SenOne, the percentage improvements with flexure hinges over conventional revolute joints are 58.6% for F_x, 57.5% for F_y and 67.44% for M_z. This represents a significant

improvement in measurement accuracy, and consequently, in the overall quality of the force-sensitive interface.

Acknowledgement

This work was developed with the contribution of the Politecnico di Torino Interdepartmental Centre for Service Robotics PIC4SeR (https://pic4ser.polito.it, accessed on 4th March 2025)).

References

[1] A. Loganathan and N. S. Ahmad, "A systematic review on recent advances in autonomous mobile robot navigation," *Engineering Science and Technology, an International Journal*, vol. 40, p. 101343, Apr. 2023, doi: 10.1016/j.jestch.2023.101343.

[2] J. A. Oroko and G. N. Nyakoe, "Obstacle avoidance and path planning schemes for autonomous navigation of a mobile robot: a review," in *Proceedings of the sustainable research and innovation conference*, 2022, pp. 314–318. Accessed: Feb. 26, 2025. [Online]. Available: https://sri.jkuat.ac.ke/jkuatsri/index.php/sri/article/view/491

[3] M. Shibata, C. Zhang, T. Ishimatsu, M. Tanaka, and J. Palomino, "Improvement of a Joystick Controller for Electric Wheelchair User," *Modern Mechanical Engineering*, vol. 5, no. 4, pp. 132–138, 2015.

[4] J. H. Choi, Y. Chung, and S. Oh, "Motion control of joystick interfaced electric wheelchair for improvement of safety and riding comfort," *Mechatronics*, vol. 59, pp. 104–114, 2019.

[5] S. Yang, S. Wang, and S. Huang, "ROS-based remote control of industrial robot joystick," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 237, no. 1, pp. 160–169, Jan. 2023, doi: 10.1177/09544062221115549.

[6] H. Kim and W. Chang, "Intuitive Drone Control using Motion Matching between a Controller and a Drone," *Archives of Design Research*, vol. 35, no. 1, pp. 93–112, 2022.

[7] A. Trujillo-León, W. Bachta, J. Castellanos-Ramos, and F. Vidal-Verdú, "Assistive handlebar based on tactile sensors: control inputs and human factors," *Sensors*, vol. 18, no. 8, p. 2471, 2018.

[8] M. Alwan, A. Ledoux, G. Wasson, P. Sheth, and C. Huang, "Basic walker-assisted gait characteristics derived from forces and moments exerted on the walker's handles: results on normal subjects," *Medical engineering & physics*, vol. 29, no. 3, pp. 380–389, 2007.

[9] R. T. DeLuca and R. A. Derenne, "Powered patient support apparatus," Dec. 05, 2017 Accessed: Feb. 26, 2025. [Online]. Available: https://patents.google.com/patent/US9833366B2/en

[10] W. Murakami, "Robot operating apparatus provided with handles for operating robot," Jun. 22, 2021 Accessed: Feb. 26, 2025. [Online]. Available: https://patents.google.com/patent/US11040456B2/en

[11] L. Tagliavini, A. Botta, G. Colucci, L. Baglieri, S. Duretto, and G. Quaglia, "Human-Machine Driving Interface for Omnidirectional Robots and Wheelchairs," in *Advances in Italian Mechanism Science*, vol. 163, G. Quaglia, G. Boschetti, and G. Carbone, Eds., in Mechanisms and Machine Science, vol. 163. , Cham: Springer Nature Switzerland, 2024, pp. 257–264. doi: 10.1007/978-3-031-64553-2_30.