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Contact sensor for robotic application

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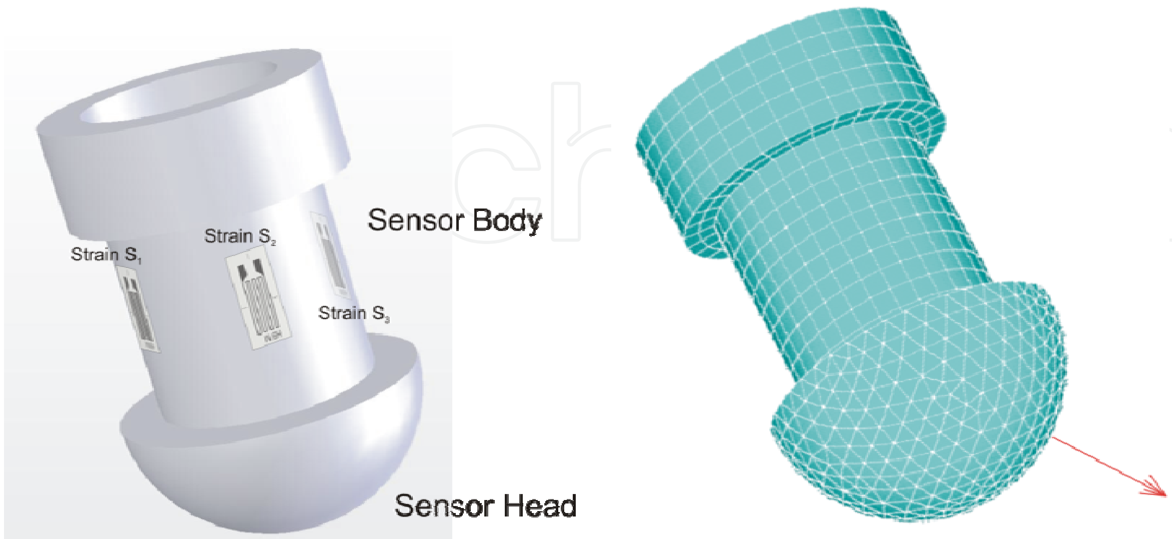
Abstract
The chapter deals with design of contact force vector sensor. The information about interaction between robotic parts and surroundings is necessary for intelligent control of robot behavior. The simplest example of such interaction is mechanical contact between working part of robot and surroundings. Than the knowledge of contact characteristic is important for robot control. This mechanical contact could be described by vector of contact force which includes information about force magnitude as well as information about orientation and contact point. The information about contact force vector will allow to predict the geometry of object which is in the contact with robots parts and modify robots behaviour. This kind of sensor can be used for instance for control of robotic hand gripping force as well as for detection of collision between robot and surrounding.

1. Introduction

The design of contact force sensor was published by Schwarzinger, 1992. This design requires application of 24 strain gauges on active part of sensor. The quantity of strain gauges is sufficient for analytical determination of contact force vector.
Demand on small size of sensor for a lot of robotic applications (Grepl, R., Bezdicek, M., Chmelicek, J., Svehlak, M., 2004) disable application of a large number of strain gauges. Quantity of applied strain gauges and their size is limiting factor for using such design in our applications.
Our design of contact sensor supposes to use only three strain gauges on active part of sensor. However three strain gauges are not enough for the analytical expression of contact force vector. Due to this fact the neural network is used for force vector identification based on measured deformations of sensor body. The application of three strain gauges and new design will reduce size of sensor but requires a lot of numerical simulations for correct and accurate sensor behaviour.
The main advantage of using neural network is in low computational requirements for vector determination. It means fast response of sensor to contact load. The neural network is able to process measured data faster than nonlinear equations for force vector expression in analytical way.
The other advantage of our design is in reduced requirements for strain measurement by strain gauges. Generally, the Wheatstone bridge has to be used for strain measurement

(Hoffman, 1989) for each strain gauge. It means that our design significantly reduces complexity of electrical measuring unit. This reduction will allow us to build in control electronics into sensor body.



a) b)

Fig. 1. Geometry of contact sensor and FE model of sensor

2. Sensor working principle

Basic principle of sensor is based on measuring of deformation of sensor body in three locations by three strain gauges on. Based on these deformations the contact force vector is identified by neural network. Huge matrix of training pairs is necessary for proper function of neural network. The training matrix contains pairs of deformations in three locations and force vectors corresponding to sensor body deformation. Finite element (FE) model of sensor was used for creating of training matrix. It is necessary to make a large number of numerical simulations with varied magnitude and position of contact force for properly work of neural network.

3. FE model of sensor

The FE model of sensor (see Fig. 1b) consists among others of sensor head, sensor body and sensor flange. The contact force is simulated as applied loads in selected nodes on sensor head. It is necessary to hold geometry and dimensions of model with real structure for correct work of sensor. Deformation of sensor during load is calculated in three positions. These positions correspond to positions of strain gauges on real sensor. For verification of FE model the force of 20N was applied on sensor head. Results of the verification are on Fig. 2 . The total strains in z-direction are S1= 2.9um/m, S2=12.6um/m and S3= -22.97um/m for this numerical simulation.

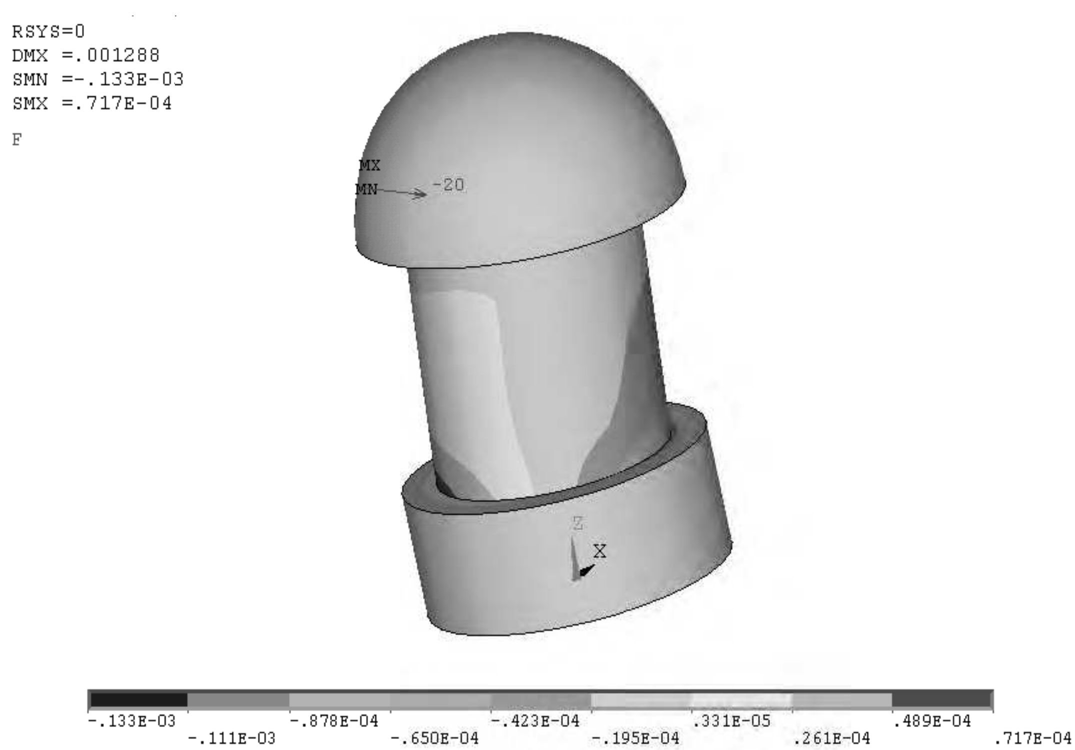


Fig. 2. Sensor deformation (applied load of 20 N) (unit of results are m/m)

4. Neural network

The architecture of artificial neural network (ANN) is shown on fig. 3. The input vector contains deformations of sensor body measured by strain gauges. The output vector contains information about contact force and position of contact force on sensor head.
The training matrix of 1000 training pairs was used for training of ANN in first step of this project. This amount of training pairs was used just for verification of functionality of suggested sensor. For better accuracy of ANN as well as sensor can by use much greater training matrix.

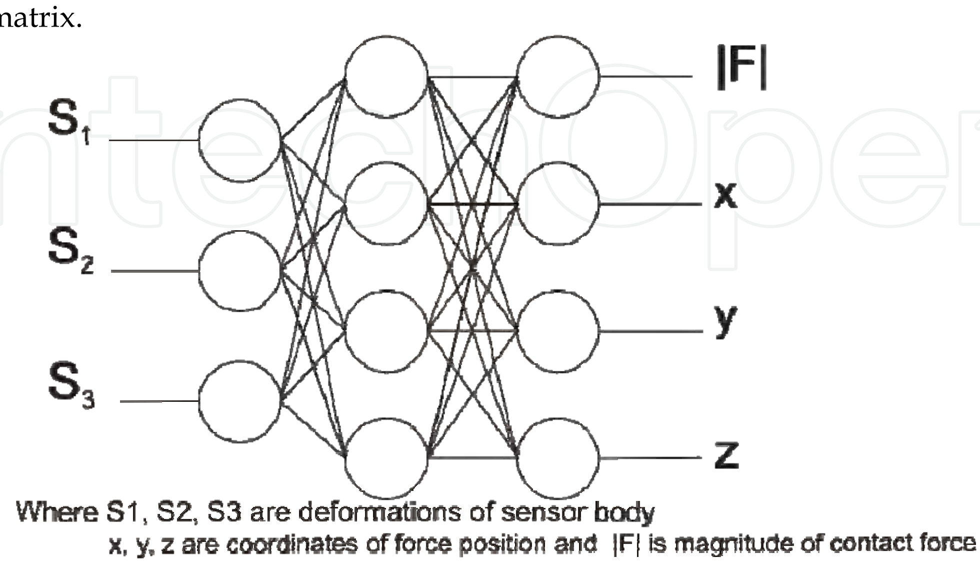


Fig. 3. Architecture of used neural network

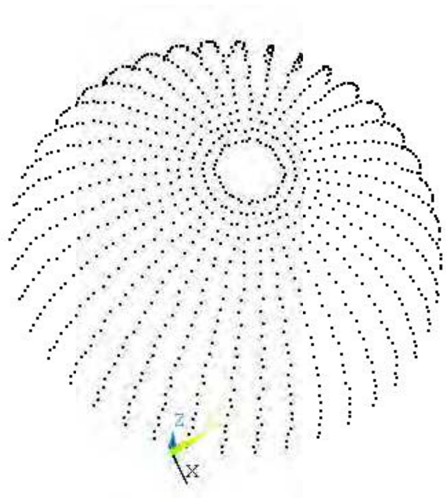


Fig. 4. Points of model load

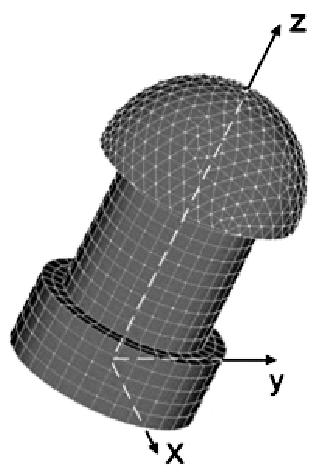


Fig. 5. Sensor coordinate system

5. Verification of ANN functionality

The force of 20N applied on sensor head was used for verification of ANN functionality. The position of the force was different than forces applied for training of ANN (points of model load used for training matrix creation are shown on Fig. 4). The x, y and z direction of applied force are 6.1mm, -3.31mm, 15.95mm respectively. The total strains in z-direction are S1=10.81um/m, S2=-23.57um/m and S3=10.04um/m. These strains were used as input vector of trained ANN. The result of contact force vector determination is in Table 1 (coordinate system of sensor is shown on .)

	Contact force coordinates		Accuracy [%]
	Point of FE model load	Position of contact force determined by Simulated by ANN	
x [mm]	6.10	6.03	98.85
y [mm]	-3.31	-3.29	99.39
z [mm]	15.95	15.97	99.87

Table 1. Result of verification

6. Experimental verification of sensor functionality

The sensor functionality was verified by experimental simulation in laboratory of Mechatronics. During experiment the loads of sensor was applied in several positions of sensor head. Gauging fixture (Fig. 6) was used for sensor positioning. Load was applied by materials testing machine Zwick Z 020-TND (Fig. 7, Fig. 8) where the real load force was measured. The deformation of sensor body was measured by strain gauges through HBM Spider 8 unit which is among other things designed for measuring of deformation by strain gauges.

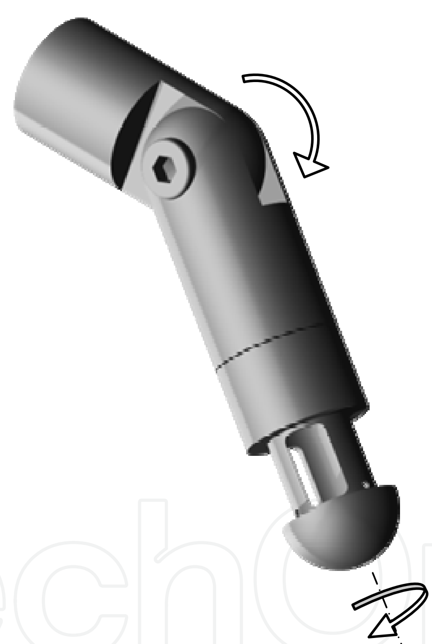


Fig. 6. Gauging fixture

Measured deformations was transferred to information about contact force position and magnitude by neural network implemented in Matlab software. The results of experimental verification for selected points are shown in Table 2 for four positions of load force and shows really good accuracy of designed sensor.

Load point	Direction [mm]	Contact force coordinates		Accuracy [%]
		Position of force during experiment	Simulated by ANN	
1	x	0.8	0.81	98.8
	y	-2.5	-2.75	91.0
	z	20.0	20.62	96.8
2	x	-1.0	-0.97	97.0
	y	-1.9	-2.03	93.6
	z	22.0	24.1	90.9
3	x	-1.0	-1.02	98.0
	y	0.1	0.11	90.9
	z	22.0	22.91	96.0
4	x	2.0	2.07	96.6
	y	-5.0	-4.52	90.4
	z	16.0	16.38	97.7

Table 2. Results of verification

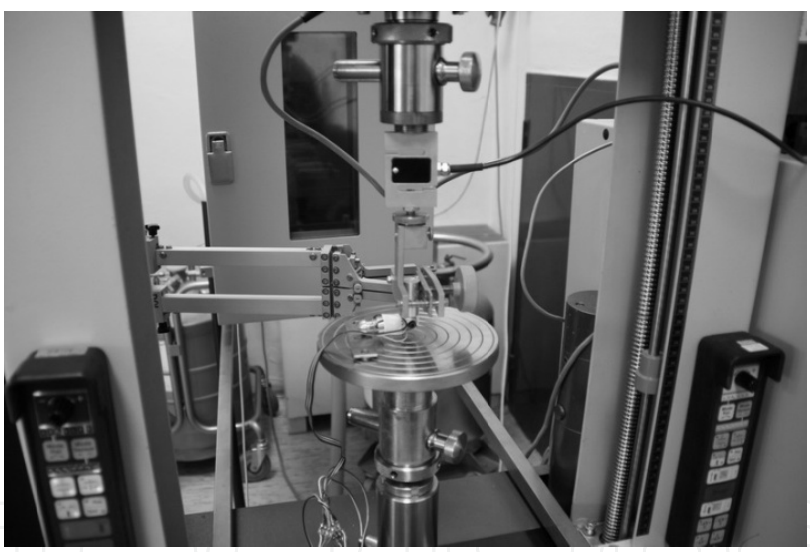


Fig. 7. Testing machine Zwick Z 020-TND

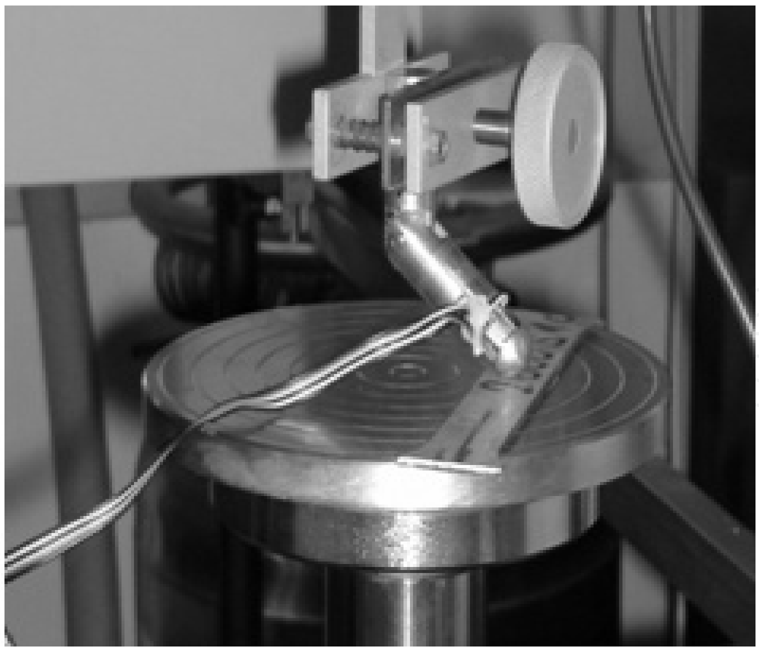


Fig. 8. Loaded sensor during experimental verification of functionality

7. Optimization of sensor design

The low sensitivity of sensor was observed in axial direction during simulations and sensor testing. Therefore the topological optimization of sensor geometry was required for increasing of sensitivity for loads applied to sensor in axial direction.

The Finite element model of sensor in finite element software ANSYS was used for topological optimization procedure. Topological optimization (ref. ANSYS) is a form of "shape" optimization, sometimes referred to as "layout" optimization. The purpose of topological optimization is to find the best use of material for a body such that an objective criterion takes on a maximum/minimum value subject to given constraints (such as volume reduction).

The sensor body is the volume which was subjected to optimization process. Volumes located under supposed locations of strain gauges was excluded from process of optimization.

This optimization was done for two load steps - for load forces oriented in different directions. The first step of optimization procedure was done for axial load of sensor head while second step was done for radial load. The result of optimization is shown for volume reduction of 80% in Fig. 10. The figure shows distribution of pseudodensity in sensor body. The boundary conditions used during optimization procedure are shown in Fig. 9.

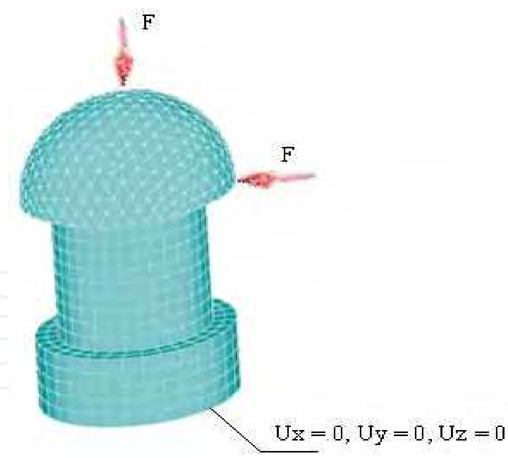


Fig. 9. Loads of sensor used in topological optimization procedure

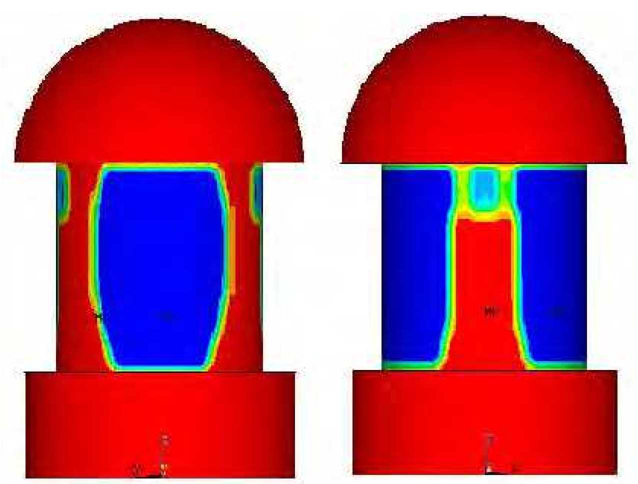
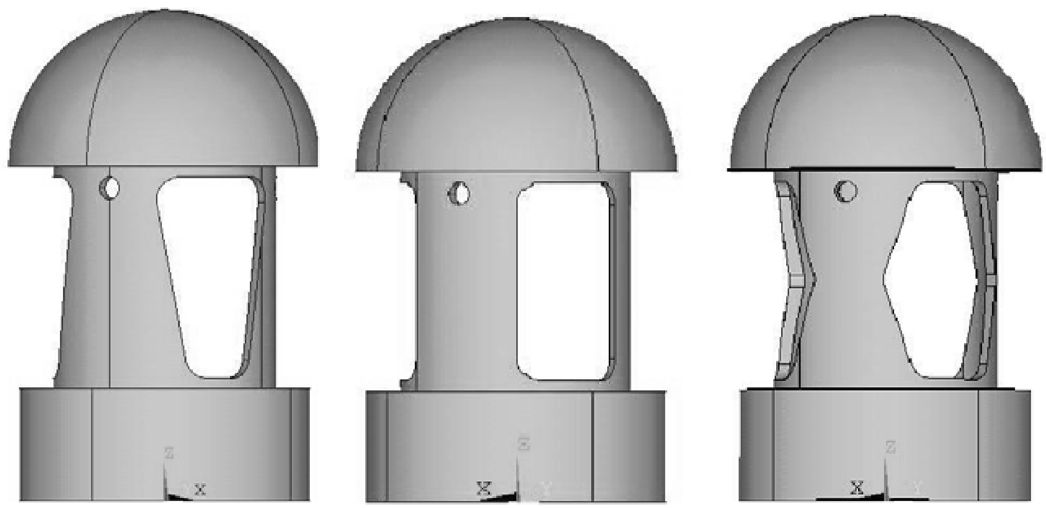


Fig. 10. Results of optimization (pseudodensity - red color means that volume will be included in final design, blue color mean that volume will be excluded from final design)

Optimized shape of sensor body need to by simplified by reason of good manufacturing. Due to this fact few shapes of cutting was designed with consideration of optimized shape (Fig. 10) and machining. Based on results of structural analysis rectangular shape of cutting with 1 mm hole (Fig. 11b)) produces the best results in terms of sensitivity. This shape is also suitable for simple machining. Fig. 12 shows prototype of optimized and non-optimized sensor which is made from aluminium alloy.



a) b) c)

Fig. 11. Optimized sensors with different shapes of cuttings

Fig. 12. Optimized and non-optimized sensor prototype

7.1. Structural analysis of sensor prototype

Structural analysis of optimized sensor was done in order to find out load limits where the linear behaviour of structure occurs. Results of this simulation are shown in Fig. 13 for load force of 140N. This value defines upper bound of sensor limits where plastic deformation of sensor body can occurs.

Fig. 13. Von-Misses stress (MPa) of sensor for load of 140 N applied in radial direction

8. Verification of optimized sensor functionality

Functionality of optimized sensor was also done by two methods. Finite elements model of sensor is used for calculation of body deformation caused by specified load in first method. The Second method using experimental verification of sensor subjected to real load. Deformations of sensor body observed by both methods are used as inputs of neural network which produces information about contact force magnitude and coordinates.

8.1. Verification of functionality by FEM simulation

Sensor functionality was proof by numerical simulation using FE model of sensor. Verification was done in same way as procedure described in section 4.
The maximal difference in load force position between force coordinates used for FEM model loading and simulated coordinates retrieved from ANN was up to 2%. This difference also shows error of trained neural network.

8.2. Experimental verification of functionality

The results of experimental verification that was done in same way as described in section 5 show that the maximum inaccuracy of sensor is up to 10%. This difference can be caused by inaccuracy in strain gauges application.

9. Conclusion

Presented chapter introduced new concept of contact sensor for robotic application that can be used to contact force vector determination. The problem of the sensor is low sensitivity for load in axial direction of sensor that was solved by topological optimization in ANSYS software. The reduction of 80% of sensor body volume was achieved and in this relation the sensitivity in axial direction increases. The functionality of sensor was proofed by numerical simulations and also by experimental verification using and simulating real load of sensor prototype. Verification was done for optimized and non-optimized prototype of sensor. Using only three strain gauges for deformation measurement of sensor body allow us to use SMD electronics parts and build up the unit to hollow sensor body. The sensor can be use for 10N to 140N load force range.

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Mechatronics, the synergistic blend of mechanics, electronics, and computer science, has evolved over the past twenty five years, leading to a novel stage of engineering design. By integrating the best design practices with the most advanced technologies, mechatronics aims at realizing high-quality products, guaranteeing at the same time a substantial reduction of time and costs of manufacturing. Mechatronic systems are manifold and range from machine components, motion generators, and power producing machines to more complex devices, such as robotic systems and transportation vehicles. With its twenty chapters, which collect contributions from many researchers worldwide, this book provides an excellent survey of recent work in the field of mechatronics with applications in various fields, like robotics, medical and assistive technology, human-machine interaction, unmanned vehicles, manufacturing, and education. We would like to thank all the authors who have invested a great deal of time to write such interesting chapters, which we are sure will be valuable to the readers. Chapters 1 to 6 deal with applications of mechatronics for the development of robotic systems. Medical and assistive technologies and human-machine interaction systems are the topic of chapters 7 to 13.Chapters 14 and 15 concern mechatronic systems for autonomous vehicles. Chapters 16-19 deal with mechatronics in manufacturing contexts. Chapter 20 concludes the book, describing a method for the installation of mechatronics education in schools.

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