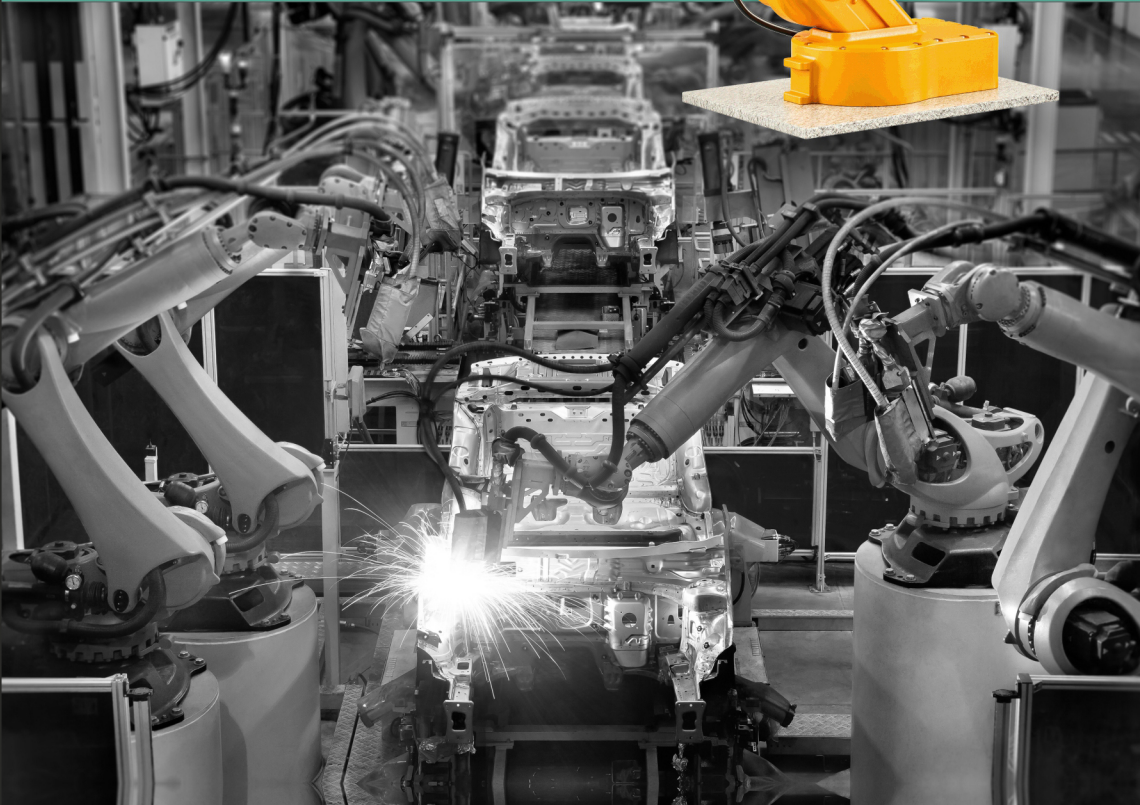


Sergey Y. Yurish, Editor



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S.Yurish
Editor

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Contents

Contents	5
Preface	11
Contributors	13
1. Electrostatic Inchworm Motors Driven by High-Voltage Si Photovoltaic Cells for Millimeter Scale Multi-Legged Microrobots...	17
1.1. Introduction	17
1.2. Multi-Legged Microrobot.....	18
1.3. Electrostatic Inchworm Motors	23
1.4. High-Voltage Si PV Cells	24
1.5. Experimental Results.....	25
1.6. Conclusions	29
Acknowledgements	29
References	29
2. Adaptive Trajectory Tracking Control and Dynamic Redundancy Resolution of Nonholonomic Mobile Manipulators	33
2.1. Introduction	33
2.2. System Description	35
2.3. Redundancy Resolution by Extended Formulation	37
2.4. Control Design	39
2.4.1. <i>Passive Control (PC) Design</i>	41
2.4.2. <i>Adaptive Passive Control (APC) Design</i>	42
2.5. Simulation Results.....	45
2.6. Conclusions	52
Acknowledgements	53
References	53
3. An Automated On-line Novel Visual Percept Detection Method for Mobile Robot and Video Surveillance.....	55
3.1. Overview	55
3.2. Introduction	55
3.3. A Percept Learning System.....	59
3.3.1. <i>Feature Generation</i>	60
3.3.2. <i>Similarity Measure</i>	62
3.3.3. <i>Percept Formation</i>	63
3.3.4. <i>Fast Search by Database Tree</i>	63
3.4. An On-line Novelty Detection Method	65
3.4.1. <i>Threshold Selection</i>	65
3.4.2. <i>Eight-Connected Structure Element Filter</i>	67
3.4.3. <i>Tree Insertion Operation</i>	67
3.5. Experiments and Results	68
3.5.1. <i>Experiment I: An Indoor Environment</i>	69
3.5.2. <i>Experiment II: An Outdoor Environment</i>	78

3.6. Conclusions	88
Acknowledgements	89
References	89

4. Dynamics and Control of a Centrifuge Flight Simulator and a Simulator for Spatial Disorientation..... 93

4.1. Introduction	93
4.2. Kinematics and Dynamics of the Centrifuge	96
4.2.1. <i>Forward Geometric Model of the Centrifuge</i>	97
4.2.2. <i>Forward Kinematics Related to the Centrifuge Velocities and Accelerations</i>	99
4.2.3. <i>Centrifuge Dynamics</i>	101
4.3. Acceleration Forces and Link Angles of the Centrifuge	106
4.3.1. <i>Calculation of the Simulator Pilot Acceleration Force Components</i> ...	106
4.3.2. <i>Calculation of the Centrifuge Roll and Pitch Angles</i>	108
4.4. The Control Algorithm of the Centrifuge Movement	109
4.4.1. <i>Calculation of the Centrifuge Arm Angular Acceleration \ddot{q}_1</i>	109
4.4.2. <i>Smoothing the Acceleration Force G Profile</i>	110
4.4.3. <i>Calculation of the Desired and Maximal Possible Values of \ddot{q}_1, \ddot{q}_2 and \ddot{q}_3</i>	111
4.4.4. <i>Centrifuge Control Algorithm (Algorithm 4.2)</i>	118
4.5. Programming Instruction of the Centrifuge Movement.....	119
4.6. Results: Verification for the Proposed Control Algorithm	120
4.7. Kinematics and Dynamics of the SDT.....	125
4.7.1. <i>Forward Geometric Model of the SDT</i>	125
4.7.2. <i>Forward Kinematics Related to the SDT Velocities and Accelerations</i>	127
4.7.3. <i>SDT Dynamics</i>	130
4.8. Acceleration Forces and Link Angles of the SDT	134
4.8.1. <i>Calculation of the SDT Simulator Pilot Acceleration Force Components</i>	134
4.8.2. <i>Calculation of the Roll and Pitch Angles of the SDT</i>	136
4.9. The Control Algorithm of the SDT Movement.....	137
4.9.1. <i>Calculation of the Maximum Possible Value of \ddot{q}_1</i>	137
4.9.2. <i>Calculation of the Maximum Possible Values of \ddot{q}_2, \ddot{q}_3 and \ddot{q}_4</i>	138
4.9.3. <i>Algorithm for Calculating the Maximum Possible Values of \ddot{q}_1, \ddot{q}_2, \ddot{q}_3 and \ddot{q}_4 Based on Approximate Forward Dynamics</i>	140
4.10. Results: Verification for the Proposed Control Algorithm	145
4.11. Conclusions	150
Acknowledgements	151
References	151

5. PCBN Tool Wear Modes and Mechanisms in Finish Hard Turning ..155

5.1. Introduction	155
5.2. PCBN Tool Materials	156
5.3. Cutting Tool Wear.....	156
5.4. PCBN Tool Wear Mechanisms.....	158
5.4.1. <i>Abrasion</i>	158

5.4.2. Diffusion and Adhesion	159
5.4.3. Built Up Layer (Chemical Reaction)	160
5.5. Factors that Influence PCBN Tool Wear	162
5.5.1. PCBN Tool Material Composition	162
5.5.2. Tool Edge Geometry	163
5.5.3. Machine Tool Requirements	165
5.6. Summary	166
References	168

6. Simulation Study of a Constant Time Hybrid Approach for Large Scale Terrain Mapping Using Satellite Stereo Imagery 171

6.1. Introduction	171
6.2. Related Work	173
6.3. Problem Formulation.....	174
6.3.1. Simulation Environment.....	174
6.3.2. Representation of the Environment	174
6.3.3. Bundle Adjustment Technique.....	175
6.3.4. Graph Weight Computation	176
6.4. Loop Closure	177
6.5. Theoretical Justification of the Hybrid Approach - Integrating RSLAM with Particle Filters	178
6.5.1. Desired Asymptotic Properties.....	178
6.5.2. Properties of Maximum Likelihood (ml) Estimators in Bundle Adjustment.....	179
6.5.3. Advantages and Asymptotic Properties of Particle Filter.....	180
6.6. Landmark-Formation in Stereo Environment.....	183
6.6.1. SURF Based Feature Detection	183
6.6.2. Landmark Characterization	185
6.7. Data Association Based on Landmark Matching.....	189
6.8. Matching Landmarks Using Fuzzy Similarity	190
6.8.1. Fuzzy Landmarks	190
6.8.2. Fuzzy Set Terminologies.....	191
6.8.3. Similarity Metric: Fuzzy Similarity	192
6.8.4. The Algorithm for Fuzzy Landmark Matching	194
6.9. Map Building	194
6.9.1. Disparity Computation.....	195
6.10. Experimental Results.....	197
6.10.1. Effect of Topographic Labelling on System Performance	198
6.10.2. Example-1	200
6.10.3. Example-2	202
6.10.4. Example-3	205
6.10.5. Simulation with Proposed Model	207
6.10.6. Comparison with Existing Models.....	207
6.11. Future Work: Improvement of the Hybrid Approach Using Auxiliary Particle Filter	207
6.12. Summary and Conclusion.....	208
Acknowledgements	209
References	209

7. An Overview of Systems, Control and Optimisation (SCO) in Recent European R&D Programmes and Projects (2013-2017) under the Emergence of New Concepts and Broad Industrial Initiatives.....	213
7.1. Introduction	213
7.1.1. <i>The Broad R&D landscape for Systems, Control and Optimisation (SCO)</i>	213
7.1.2. <i>Structure of the Paper and Profiling of Projects</i>	215
7.1.3. <i>Topics in Projects vs. Topics Supported by Key Scientific Societies</i>	216
7.1.4. <i>Mapping Projects Content According to Inherent Single, or Multiple Innovations</i>	216
7.1.5. <i>The Sample of R&D Projects Considered</i>	218
7.2. Systems, Control, Control Systems, Control in Systems and “No-control”....	219
7.2.1. <i>Terminology, Evolution, Explanations, Different Views</i>	219
7.2.2. <i>Another Consideration: Focus on Control vs. Focus on Applications (as addressed in Projects)</i>	224
7.2.3. <i>The Important Role of Sensors and Actuators</i>	225
7.2.4. <i>Challenges for Systems and Control Other Than Explicit Feedback Arrangements of Fig. 7.4</i>	227
7.3. The European R&D scene: European Commission, National & Other Programmes	228
7.3.1. <i>Outline</i>	228
7.3.2. <i>The Main R&D&I Programmes in the European Union (EU)</i>	229
7.3.4. <i>National and Other Programmes</i>	232
7.3.5. <i>Renewal of R&D Programmes</i>	233
7.3.6. <i>Views and some criticism about the Control Domain</i>	237
7.3.7. <i>What Communities Deal with Systems and Control R&D?</i>	239
7.4. Project Categories and Examples Regarding Systems, Control and Optimisation	240
7.4.1. <i>Preliminary Remarks</i>	240
7.4.2. <i>Project Examples, According to Their SCO Content, a Bottom up View</i>	240
7.4.3. <i>SCO Topics in Large Scale and Broad Scope Projects</i>	245
7.4.4. <i>Aerospace Research and SCO Topics</i>	248
7.4.5. <i>Alternative and Other Interesting SCO Applications</i>	249
7.5. Concluding Remarks and new challenges	252
Summary	254
References	255
Appendix	265
7.A1. Additional Information on Selective Project Groups in SCO Topics.....	265
7.A2. Project Groups	265
7.A2.1. <i>Algebraic and Geometric Methods (See Also under PDEs Group Below)</i>	265
7.A2.2. <i>Automata-based System Design</i>	266
7.A2.3. <i>Dynamical Systems</i>	268
7.A2.4. <i>Non-linear Systems and Bifurcations</i>	269
7.A2.5. <i>Complex Systems</i>	271
7.A2.6. <i>Formal Methods</i>	272
7.A2.7. <i>Consensus Methods (Including Non-ICT / Non-engineering Systems)</i>	278

7.A2.8. PDEs, System Modelling (e.g. Control for Wave, -HD, -MHD Equations)	281
7.A2.9. Symbolic Control	284
7.A2.10. Robotics	286
7.A2.11. Self Organisation & Self-assembling Systems	290
7.A2.12. Decision Making/Processes, Markov DP, POMDP, Multi-agents Systems	290
7.A2.13. Control of Embryonic Stem Cells Systems - Regulatory Systems.....	291
7.A2.14. Advanced Controller Synthesis - Novel Concepts and Methods	292
8. Model Detection Using Innovations Squared Mismatch Method: Application to Probe Based Data Storage System.....	297
8.1. Introduction	297
8.2. Real Time Plant Detection with Innovations Squared Mismatch (ISM)	299
8.2.1. Preliminaries, Problem Formulation and MAP	300
8.2.2. Innovations Squared Mismatch (ISM)	302
8.3. Plant Detection with Known Dwell Interval; Sequence Detection	305
8.4. Application of ISM and ISM-MLSD to Probe Based Data Storage	306
8.4.1. Validation of Equivalent Model and Detection Framework.....	309
8.4.2. Detection Performance from Experiments	313
8.4.3. Symbol by Symbol and Sequence Detection	314
8.5. Conclusions	316
References	317
9. H_∞ Tracking Adaptive Fuzzy Sliding Mode Design Controller for a Class of Non Square Nonlinear Systems	319
9.1. Introduction	319
9.2. Generalized Conventional Sliding Mode.....	322
9.3. Design of a Robust Adaptive Fuzzy Controller	327
9.4. Simulation Results.....	339
9.5. Conclusion.....	354
References	355
10. Analytical Solution of Optimized Energy Consumption of Induction Motor Operating in Transient Regime.....	359
10.1. Minimization of a Cost-to-go Function under Constraints	359
10.1.1. Statement of Optimal Control Problem with a Final Free State	359
10.1.2. Reformulation of the Optimal Control Problem	361
10.2. Optimal Control via the Hamilton-Jacobi-Bellman Equation.....	363
10.2.1. Determination of the HJB Equation	363
10.3. Determination of the HJB Equation in the Case of IM Minimum Energy Control.....	367
10.3.1. Solving the HJB Equation	370
10.4. Implementation of the Optimal Solution Obtained by HJB Equation	382
10.4.1. Determination of the Rotor Flux Optimum Trajectory.....	382
10.4.2. Implementation of the Flux Optimal Trajectory in the VECTOR CONTROL Structure	385

10.5. Conclusion.....	393
References	394
Index	397

Preface

By 2020 the International Federation of Robotics (IFR) estimates that more than 1.7 million new industrial robots will be installed in factories worldwide and robots for domestic could reach almost 32 million units in the period 2018-2020, with an estimated value of about €10 bn (\$11.7 bn).

Industrial robots offer many benefits, including cost reduction, increased rate of operation and improving quality, along with improved manufacturing efficiency and flexibility. The demand for industrial robotics is majorly observed in industries such as automotive, electrical & electronics, chemical, rubber & plastics, machinery, metals, food & beverages, precision & optics, and others. In its turn, industrial automation control market will witness considerable growth during the same period with the growing demand of products such as sensors, drives and various robots.

The first volume of the *Advances in Robotics and Automatic Control: Reviews*, Book Series started by IFSA Publishing in 2018 contains ten chapters written by 32 contributors from 9 countries: Belgium, China, Germany, India, Ireland, Japan, Serbia, Tunisia and USA.

Chapter 1 discusses the electrostatic inchworm motors with low energy consumption using a small size power source. The leg of the microrobot is designed to allow reciprocal motions and powered by Si photovoltaic (hereafter PV) cells.

Chapter 2 describes an adaptive trajectory tracking control for nonholonomic mobile manipulators under modeling uncertainties and external disturbances. One feature of the proposed controller is its model-independent control scheme that can avoid the knowledge of the dynamic parameters and the bound of the external disturbances. Furthermore, the control law is formulated in task space and the redundancy problem is resolved by an extended approach.

Chapter 3 presents a fast approximate nearest neighbor search tree based novelty filter for mobile robotic and video surveillance applications.

Chapter 4 describes control algorithms for the centrifuge flight simulator/spatial disorientation trainer, calculate their kinematic and

dynamic parameters in each interpolation period to predict their dynamic behaviour.

Chapter 5 presents state-of-the-art review in the area of continuous hard turning. The various wear mechanisms of polycrystalline cubic boron nitride tool materials are discussed with a view to identifying the critical factors that determine their behaviour in application.

Chapter 6 discusses an approach, which involves factorization of the SLAM posterior over the robot's path, in which each individual particle follows a constant time stereo SLAM approach and the particle distribution is harnessed by the algorithm to estimate the optimal trajectory.

Chapter 7 reports topics in Systems, Control and Optimisation and their evolution through recently funded projects, since about 2013, as well as the EU (e.g. H2020, ERC), National and other Programmes vis-à-vis broader developments.

Chapter 8 summarized a real time switching-model detection Innovation Squared Mismatch (ISM) strategy is presented to enable closed loop control of the switched systems.

Chapter 9 reports H_∞ tracking adaptive fuzzy sliding mode design controller for a class of non square nonlinear systems.

Chapter 10 discusses two formulations of the optimal control problem associated with the optimization of the energy consumed by the induction motor under vector control. The emphasis was placed on the advantage of limiting the control quantities during a real application in order to protect the actuators and the machine.

I hope that readers will enjoy this book and it can be a valuable tool for those who involved in research and development of various robots and automatic control systems.

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Editor

Barcelona, Spain

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Chapter 1

Electrostatic Inchworm Motors Driven by High-Voltage Si Photovoltaic Cells for Millimeter Scale Multi-Legged Microrobots

Ken Saito, Daniel S. Contreras, Isao Mori, Daisuke Tanaka, Satoshi Kawamura, Taisuke Tanaka, Minami Kaneko, Fumio Uchikoba, Yoshio Mita, Liwei Lin and Kristofer S. J. Pister

1.1. Introduction

Several microrobot systems from the micrometer to centimeter scale have been demonstrated [1-12]. Among these demonstrations, the micrometer scale ones have potential usages in special environments such as surgery inside the narrow blood vessel of a human brain or micro assembly for the small size mechanical system [4, 8] but it is difficult to add power sources and controllers into the microscale system. Therefore, passive control schemes by external electrical or magnetic forces are commonly implemented. On the other hand, a lot of centimeter-size robots have been constructed by the miniaturizations of electrical components with integrated sensors, actuators, power sources and controllers [6, 9]. Despite the fact that multiple bio-inspired robots have been proposed, millimeter scale robots do not perform like insects due to the difficulty in integrating power sources and actuators onto the robot [13-14]. In particular, the locomotion mechanisms of insects attract the attention of researchers [5, 7]. In seeking further miniaturization, some researchers use micro fabrication technology to fabricate small sized actuators [15-16]. For example, piezoelectric actuators, shape memory alloy actuators, electrostatic actuators, ion-exchange polymer actuators, and so on are a few examples. These actuators have different strengths, such as power consumption, switching speed, force generation, displacement, and fabrication difficulty. In general, an actuator can only

generate either rotary or linear motion and mechanical mechanisms are necessary to convert the movements generated by the actuators to locomotion.

Previously, the authors have shown a millimeter scale hexapod-type microrobot to perform the tripod gait locomotion of an ant [17], and a quadruped-type microrobot to replicate the quadrupedal gait locomotion of an animal [18] by using shape memory alloy actuators for large deformation and large force. This chapter discusses the electrostatic inchworm motors [19-21] with low energy consumption using a small size power source. The leg of the microrobot is designed to allow reciprocal motions and powered by Si photovoltaic (hereafter PV) cells [22].

1.2. Multi-Legged Microrobot

Fig. 1.1 (a) shows the previous multi-legged microrobot using shape memory alloy type actuator [18]. A previous multi-legged microrobot using shape memory alloy actuator is changed to electrostatic inchworm motors in this work, where each leg of the robot can perform the stepping motion via a single actuator. The leg is fixed on both sides of the body and the microrobot can increase the number of the legs easily. In this chapter, the actuator connection part has been redesigned to accommodate the electrostatic inchworm motors. Fig. 1.1 (b) shows the mechanical parts of the leg made from a silicon wafer except for the shaft and the steady pin. The shapes of the mechanical parts are machined by the inductively coupled plasma dry etching process with photolithography technology. The authors have manual assembled the mechanical parts of the robot because microfabrication technology is hard to construct the complicated three-dimensional structure. In the process, 200 μm -thick silicon wafers were used for the mechanical parts except for the washer which used 100 μm -thick silicon wafers. The shaft was constructed by using 0.1 ± 0.002 mm in diameter cemented carbide. The washer was mounted to the end of a shaft to fix the silicon parts. To keep the parts rigidly connected, the washer and the shaft were glued using cyanoacrylate. All silicon parts have a clearance of a 10 μm gap with respect to the other fitted parts. Since these actuators can only generate the rotary motion or linear motion, linkage assemblies are needed for a microrobot to move using the stepping pattern. The stepping pattern realized by two sets of four-bar linkages. Bar 1, bar 2, bar 5 and bar 6 are the primary (top) four-bar linkage. Bar 3, bar 4, bar 5 and bar 6

are the secondly (bottom) four-bar linkage. The primarily four-bar linkage and secondly four-bar linkage are combined with each other with bar 5 and bar 6 (Fig. 1.1 (c)).

Fig. 1.2 shows the leg motion and trajectory of the leg. The inflection point of the trajectory has four points such as (x_1, y_1) , (x_2, y_2) , (x_3, y_3) and (x_4, y_4) . The steady pin and the hole of bar 5 cause the inflection of the trajectory. The four points can be expressed by the difference of angles of θ_A and θ_{Foot} . The difference of θ_A and θ_{Foot} can perform the reciprocal movement of point P. In other words, Fig. 1.2 shows that the designed leg can perform the stepping motion by the reciprocal movement of point P.

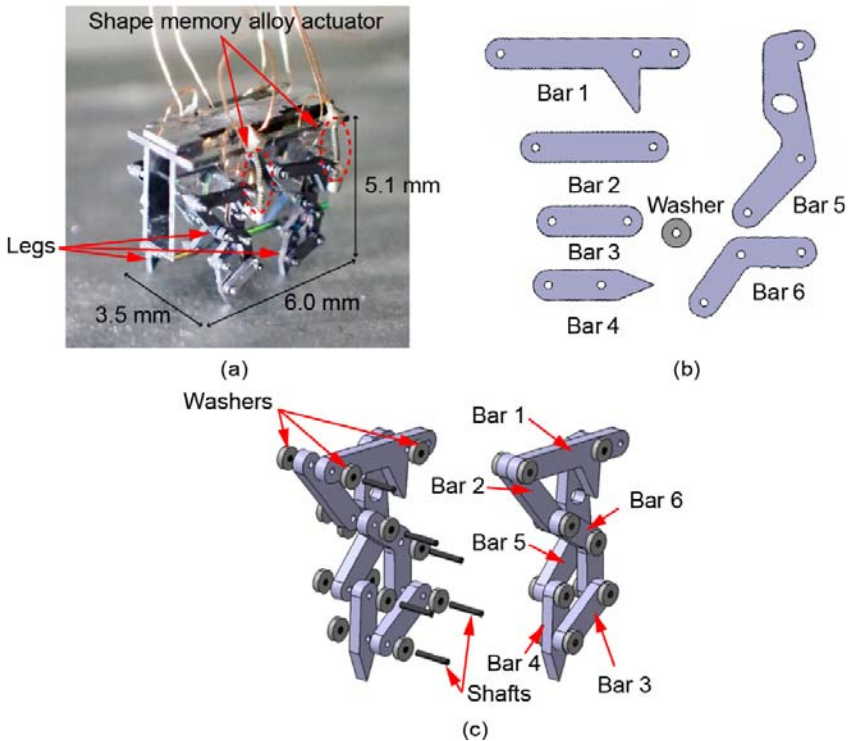


Fig. 1.1. (a) Previous multi-legged microrobot using shape memory alloy type actuator [18]. Mechanical parts of the leg for microrobot with (b) individual parts; (c) assembled structure.

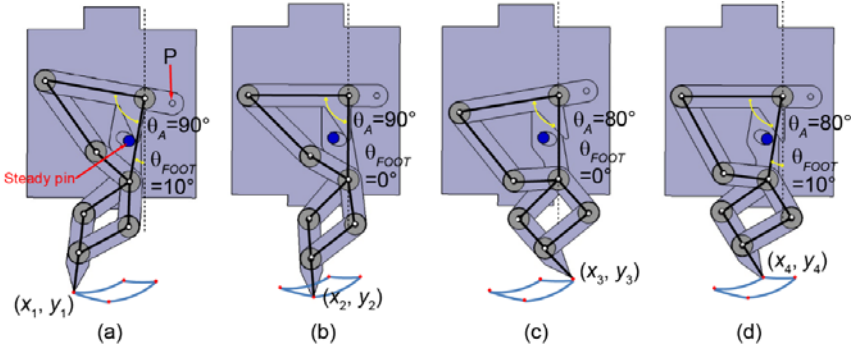


Fig. 1.2. Leg motion and trajectory of the leg. (a) (x_1, y_1) at $\theta_A=90^\circ$, $\theta_{FOOT}=10^\circ$; (b) (x_2, y_2) at $\theta_A=90^\circ$, $\theta_{FOOT}=0^\circ$; (c) (x_3, y_3) at $\theta_A=80^\circ$, $\theta_{FOOT}=0^\circ$; (d) (x_4, y_4) at $\theta_A=80^\circ$, $\theta_{FOOT}=10^\circ$.

The authors design the mechanical parts of the leg according to the mathematical equations. Fig. 1.3 and Table 1.1 show the conditions to describe the point of the leg (x_n, y_n) . The (x_0, y_0) is the origin coordinate which is the only fixed point of the robot. The upper case alphabet A, B, C, D, E, F, G, H and I show the name of each lengths. L1 and L3 show the auxiliary lines from (x_0, y_0) to bar 4 which is the bar contains the point of the leg. $\theta_3, \theta_5, \theta_7, \theta_B$ and θ_{A0} are described as Fig. 1.3 (b).

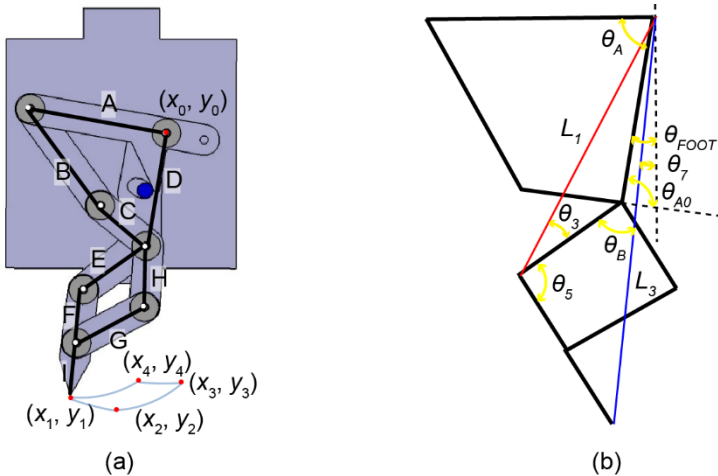


Fig. 1.3. Name of each bars, coordinates and angles of the leg. (a) Length and coordinates; (b) Angles and auxiliary lines.

Table 1.1. Length between the node points.

Name of bar	Name	Length (μm)
Bar 1	A	1800
Bar 2	B	1556
Bar 6	C	800
Bar 5	D	1500
Bar 5	E	1000
Bar 4	F	700
Bar 3	G	1000
Bar 6	H	800
Bar 4	I	700

The (x_n, y_n) ($n=1, 2, 3, 4$) can describe by the Equation (1.1):

$$(x_n = L_3 \cos(-90^\circ - \theta_7 - \theta_{Foot}), y_n = L_3 \sin(-90^\circ - \theta_7 - \theta_{Foot})), \quad (1.1)$$

where $\theta_7, L_3, L_1, \theta_5, \theta_3, \theta_B$ and θ_{A0} are the following Equation (1.2), (1.3), (1.4), (1.5), (1.6), (1.7) and (1.8), respectively.

$$\theta_7 = \cos^{-1} \frac{L_1^2 + D^2 - E^2}{2L_1D} - \cos^{-1} \frac{L_1^2 + L_3^2 - (F+I)^2}{2L_1L_3}, \quad (1.2)$$

$$L_3 = \sqrt{L_1^2 + (F + I)^2 - 2L_1(F + I)\cos(\theta_3 + \theta_5)}, \quad (1.3)$$

$$L_1 = \sqrt{D^2 + E^2 - 2D^2 \cos 135^\circ}, \quad (1.4)$$

$$\theta_5 = \cos^{-1} \left(\frac{E - H \cos \theta_B}{\sqrt{E^2 + H^2 - 2EH \cos \theta_B}} \right) + \cos^{-1} \left(\frac{E^2 + H^2 - G^2 + F^2 - 2EH \cos \theta_B}{2F\sqrt{E^2 + H^2 - 2E \cos \theta_B}} \right), \quad (1.5)$$

$$\theta_3 = 180^\circ - \left(135^\circ + \cos^{-1} \frac{L_1^2 + D^2 - E^2}{2L_1D} \right), \quad (1.6)$$

$$\theta_B = 360^\circ - (\theta_{A0} + 135^\circ + 50^\circ), \quad (1.7)$$

$$\theta_{A0} = 180^\circ - \left(\cos^{-1} \left(\frac{D - A \cos \theta_A}{\sqrt{D^2 + A^2 - 2DA \cos \theta_A}} \right) + \cos^{-1} \left(\frac{D^2 + A^2 - B^2 + C^2 - 2DA \cos \theta_A}{2C\sqrt{D^2 + A^2 - 2DA \cos \theta_A}} \right) \right), \quad (1.8)$$

Table 1.2 shows the derived coordinates of the each foot point using the above equations and conditions. This result shows the designed leg can perform the stepping motion which is needed to move the multi-legged microrobot.

Table 1.2. Coordinates of each foot point.

Foot point	θ_A and θ_{Foot}	Coordinates
(x_1, y_1)	90° and 10°	$(-1248.6, -3440.3)$
(x_2, y_2)	90° and 0°	$(-632.3, -3604.9)$
(x_3, y_3)	80° and 0°	$(227.2, -3249.4)$
(x_4, y_4)	80° and 10°	$(-340.5, -3239.5)$

Fig. 1.4 shows the measurement method for the required force F_S to actuate the leg. The required force can describe by the Equation (1.9):

$$F_S = M_W g, \tag{1.9}$$

where M_W is the mass of the weight and g is the gravity acceleration. The authors vary the mass of the weight to find the minimum weight to actuate the leg. Fig. 1.4(a) is the required force for the push motion.

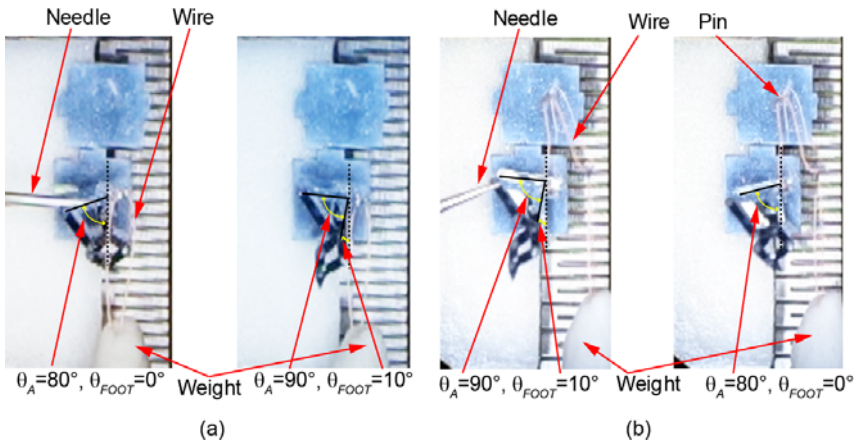


Fig. 1.4. Measurement method for the required force to actuate the leg for (a) push motion; (b) pull motion.

The weight was attached to point P of bar 1 using a wire. The required force of 542 μN is measured in order to move the leg to the regular position under the lightest weight of 55.3 mg. Fig. 1.4 (b) shows the required force for the pull motion. The weight was attached to the point P of bar 1 using a wire through the pin and the lightest weight was 36.2 mg, while the force for this pull motion was 355 μN .

1.3. Electrostatic Inchworm Motors

As an alternative low-power means of actuation, electrostatic inchworm motors can be used to drive the legs of the microrobot. MEMS electrostatic inchworm motors are based on capacitively driven gap-closing actuators (GCA) working in tandem to displace a shuttle linearly at over 100 μN force output without any static current [19].

The authors used an angled-arm design based on work from [20]. In this design, the GCAs use an attached angled-arm to impact a central shuttle and move it in a preferential direction. The motors have a gap size of 2.1 μm and each step of the motor moves the shuttle by 1 μm . Each GCA has 70 fingers, totalling 140 fingers for each actuation step. The inchworm motor chiplet measures a total area of approximately 2.2 mm \times 2.5 mm. The electrostatic inchworm motors are fabricated in a 3-mask silicon-on-insulator (SOI) process. The SOI wafers had a 40 μm device layer, 2 μm buried oxide and 550 μm handle wafer. A layer of 100 nm-thick aluminium is deposited on the device-layer silicon to define the contact pads. The device layer silicon is etched to form the structure of the motors using DRIE. A backside etch is then performed to reduce the mass and release the singulated chiplets from the substrate.

Fig. 1.5 shows the force output of an electrostatic inchworm motor. Force measurements are taken using a serpentine spring assembly attached to the motor shuttle. The serpentine assembly has a spring constant of 18.5 N/m. By measuring the displacement of the inchworm shuttle, we can relate this to the force output of the motor. The solid line highlights the analytical calculation of the force output. We can see that at 60 V we get an average force output of over 1 mN from 5 measured devices. The original angled-arm inchworm motors shown in [20] were able to generate 1.88 mN at 110 V. Previous work has shown 500 μN of force at 60 V [21] while the newly fabricated devices have demonstrated 1 mN of force at 60 V. Discrepancies between the analytical model and the

measured values can be attributed to unaccounted lateral etching of the silicon sidewalls. This can increase the effective finger gap size and change the spring constants of the springs.

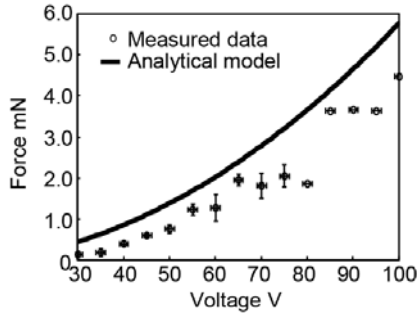


Fig. 1.5. The raw force output of the inchworm motor used in these experiments.

1.4. High-Voltage Si PV Cells

Fig. 1.6 shows the fabricated high-voltage Si PV cell array. The PV cell array was designed in an area of about 3 mm square. The device was made by CMOS post-process dry release and device isolation method. The array consists of 125 PV cells connected in series and each cell has a p-diffusion layer on n-well. The details of the design and process method are shown in reference [22].

In the reference [22], the light source of the PV cell array was a red LED with 30 mA current. The open circuit voltage (VOC) was 57.9 V, from which we can deduce that the open circuit voltage of each cell was about 0.46 V on average. The short circuit current (ISC) was 976 nA. The maximum power (Pmax) was 43.3 μ W, where the voltage was 53.2 V and the current was 683 μ A. The fill factor (FF; $FF = P_{max}/V_{OC} I_{SC}$) was 76.7 %. The FF generally indicates the quality of the pn-junctions (a high fill factor means a high quality of the junction) and the value 76.7 % is relatively high. This high value was achieved by using a commercial CMOS process performed by a foundry. However, the maximum power in the reference [22] was not high enough to actuate the electrostatic inchworm motors. The authors changed the light source to a xenon lamp with 5 A current to achieve $V_{OC}=60.0$ V and $I_{SC}=105$ μ A. Fig. 1.7 shows the I-V characteristics of the PV cell array lighted with the xenon

lamp. The xenon lamp irradiated the PV cell from a distance of 10 cm. This result shows that the xenon lamp can produce 30 times the power shown in the reference [22], large enough to actuate the electrostatic inchworm motors.

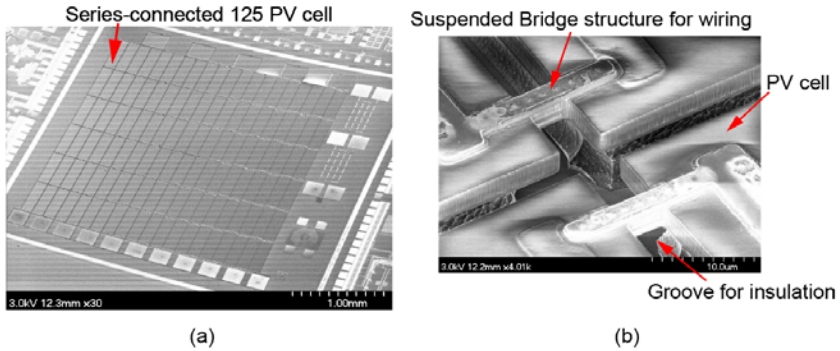


Fig. 1.6. Fabricated PV cell array [22]. (a) Whole view; (b) Magnified view.

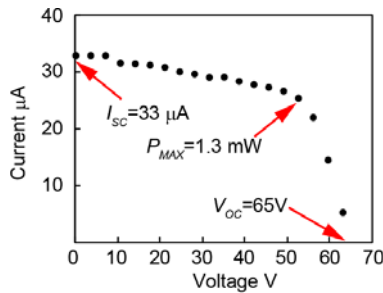


Fig. 1.7. I-V curve of 125-cell PV array (Light source: xenon lamp).

1.5. Experimental Results

Fig. 1.8(a) shows an inchworm motor chip. The image highlights the ring meant to engage to a complimentary post on the leg, the gap closing actuators, the reset spring, and the signal pads that receive signals from the drive circuit. The inchworm motor is fabricated in the 3-mask process described in Section 1.3. This motor has the force profile shown in Fig. 1.5. Fig. 1.8 (b) highlights the methodology of integration of the inchworm chip with the leg. The motor is taped onto a platform off of a

micromanipulator stage. This is because aligning the ring with the post and interfacing the parts require careful precision. Once the leg engagement ring is in place on the leg post, a set of probes are dropped onto the motor contact pads to provide the electrical signals from the circuit needed to drive the motor. This circuit is powered by the solar cell.

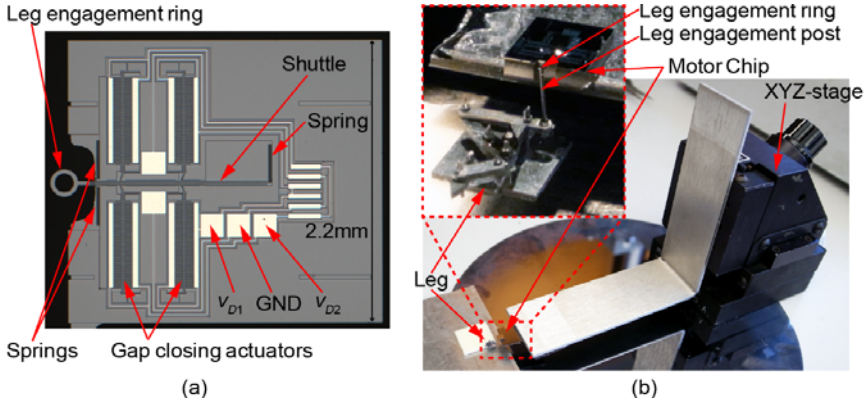


Fig. 1.8. Details of the inchworm motor chip integration (a) A micrograph of the motor chip highlighting the leg engagement ring, gap closing actuators, shuttle, spring, and the electrical contact pads. The pads are driven with probes that are connected to the circuit that is driven by the solar cells; (b) A diagram of the experimental setup showing the leg engagement post, meant to interface with the leg engagement ring. The motor chip is held on a platform on a micromanipulator stage and the ring is maneuvered around the post. Once the motor is in place, the probes are dropped onto the motor chip to drive the leg.

Fig. 1.9 shows the actuation experimental setup of the electrostatic inchworm motors using PV cell array (Fig. 1.9 (a)). The anode-side of PV cell array was connected to the solid resistor at the collector of the transistor. In other words, the generated voltage by the PV cell, V_{PV} , was used as the voltage source of the circuit. The Arduino was used for switching the transistor for generating the driving waveform v_{D1} and v_{D2} for the electrostatic inchworm motors (Fig. 1.9(b)). The driving waveforms were two offset 60 V amplitude 500 Hz square waves, one for each of the GCAs of the motor.

Fig. 1.10 shows the generated force of the electrostatic inchworm motors. The force gauge system was attached on the shuttle and the scale

of the force gauge was characterized as 1 dot = 0 μN , 2 dot = 370 μN , 3 dot = 740 μN . The guideline is attached to the shuttle to point the dot. The result in Fig. 1.11 shows that the guideline points the 3 dot. This result shows the generated force was 740 μN according to the gauge system, which is high enough to actuate the leg of the microrobot.

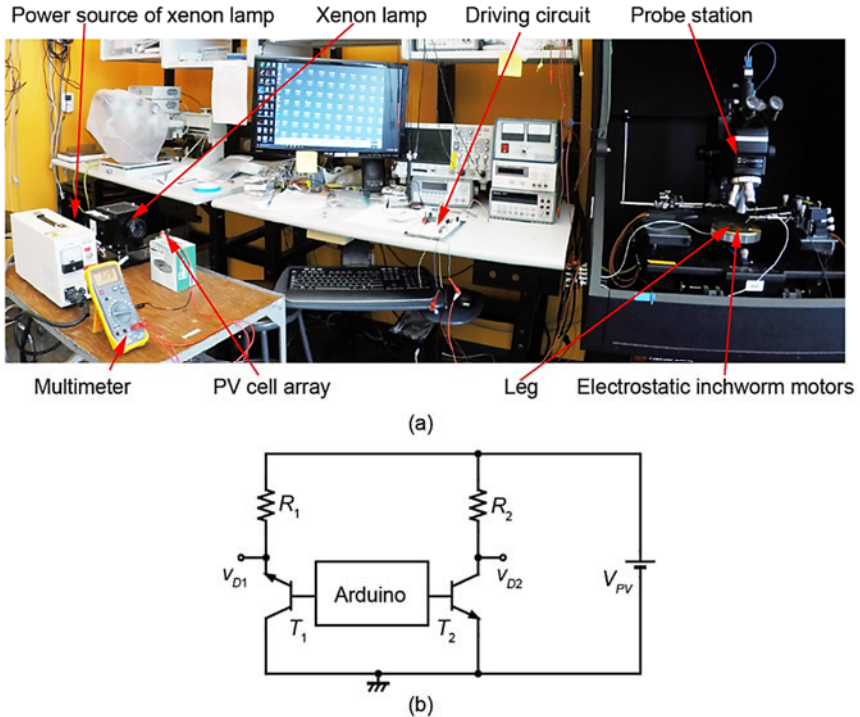


Fig. 1.9. Actuation experimental setup: (a) Whole setup; (b) Circuit diagram of driver circuit.

Fig. 1.11 shows the actuation of the leg using electrostatic inchworm motors. The ring structure was attached to the shuttle of the electrostatic inchworm motors using the method described above. The electrostatic inchworm motors was connected to the leg through the shaft of point P. The result in Fig. 1.11 shows that the electrostatic inchworm motors produced about 250 μm in displacement to move the leg of the microrobot. However, the pull motion was not enough to actuate the leg from (x_4, y_4) to (x_1, y_1) . This is because spring was designed to generate

the 250 μN pull motion. The pull motion needs 355 μN to complete the motion. The strength of the spring needs for the future examination.

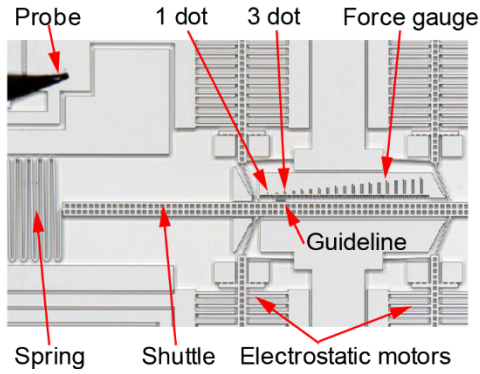


Fig. 1.10. Generated force measurement of the electrostatic inchworm motors.

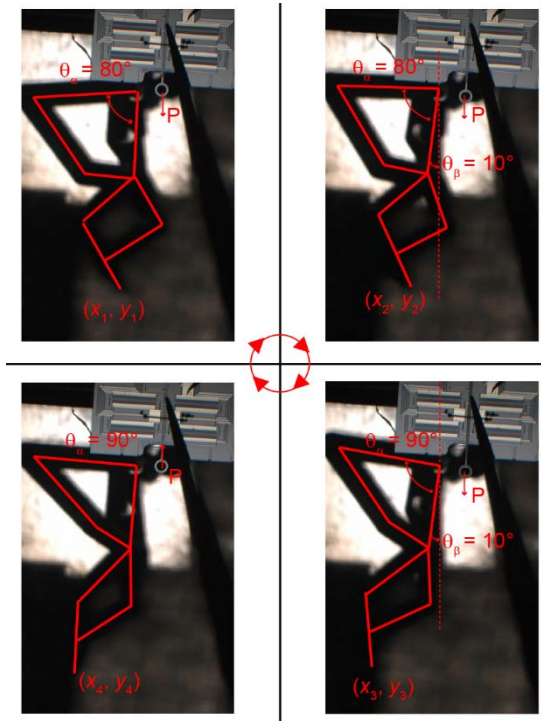


Fig. 1.11. Actuation of leg: (a) Pull motion; (b) Push motion.

1.6. Conclusions

In this chapter, the electrostatic actuator with low energy consumption is powered by a 3 mm × 3 mm Si photovoltaic cells with an output voltage of 60 Volts. The generated force of the electrostatic inchworm motors was 740 μN to actuate the leg of the microrobot. The leg of the microrobot could move using the electrostatic inchworm motors with proper driving waveforms for large displacements. In the future, the authors will design the millimeter scale locomotive robot with Si PV cell driven electrostatic inchworm motors.

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Index

A

abnormality, 62
 acceleration force, 105
 actuators, 17-19, 24, 27, 28, 245
 adaptive, 36, 38, 43, 46
 adaptive fuzzy controller, 346
 aerospace SCO projects, 272
 Algebraic and Geometric Methods, 288
 angular accelerations, 112, 142
 approximate inverse and forward dynamics of the robot, 155
 ARTEMIS (Embedded Systems ETP), 250
 asynchronous motor, 413
 Atomic force microscope, 323
 automata, 239, 241, 274, 289, 290
 Automata, 289
 Automatic Control, 345
 autonomous
 robot, 66
 ships, 265
 auxiliary particle, 189, 226

B

backstepping, 37
 bag-of words, 194
 Bias-compensated exponentially weighted recursive least square (BCEWRLS), 332
 Bifurcations, 263, 292
 Blunder Detection, 215
 bundle
 adjustment, 187, 189, 190, 192, 193, 195-197, 199, 227, 228
 distribution, 187

C

centrifuge
 flight simulator, 105
 pitch angle, 121
 roll angle, 121

challenges (SCO), 275
 chattering phenomenon, 379
 Chi-square statistic (χ^2), 85
 City-block distance. see L1-norm, see L1-norm, see L1-norm
 closed-cycle
 motor drive, 397
 process, 397
 Cloud, Edge,Fog, 267
 clustering method, 71
 color histogram, 67, 69
 Communities (dealing with SCO), 260
 compensation, 37, 38
 Complex
 Adaptive Systems (CAS), 241, 254, 295
 Systems (projects), 294
 computation efficiency, 64
 computational complexity, 63
 computer vision, 66, 67
 Consensus (Methods), 301
 constant time, 187, 189, 190, 226
 continuous relative
 representation(CRR), 190
 Contractual PPPs, 252
 Control, 36, 43, 44, 46
 control (of complete plants), 265
 Control (projects), 264
 Control Domain (Views about), 258
 control information, 190
 Control systems design, 266
 control vector, 391, 393
 Controller Synthesis, 274, 316
 conventional VECTOR CONTROL, 416, 418-420
 COOL (Method / tools), 275
 Cooperation (control, computing and communications), 260
 cost-to-go function, 387, 393, 396
 CPS, 258
 Cramer's V value, 86
 cross products of inertia, 114
 cross-sectoral programmes, 237
 CRR graph, 193
 Cryogenic systems, 264

D

Data Association, 206
decision
 boundary, 62, 64, 92
 Making (projects), 314
 support systems (DSS), 243
decision-making, 266
descriptor, 69, 72
differential equation, 399, 402, 404,
 405, 409
digital video camera recorder, 78, 89
dimensionality, 63, 64, 71, 92
discrete systems, 239, 253
Disparity, 213, 214
disturbances, 36, 38, 43, 44, 46, 48-58
driving waveform, 28, 31
Dynamic, 36
Dynamical Systems (projects), 291

E

efficient SVDD, 64
EKF filters, 187
electrostatic inchworm motors, 18, 24,
 25, 26, 28-31
Enterprise ICT, 267
environment size, 190
Equivalent dynamics, 332
estimator, 189, 195, 196, 197, 199,
 200, 201
Euler-Lagrange equation, 387
European
 Defence Agency (EDA), 253
 Science Foundation (ESF), 250
 Technology Platforms, 237, 249

F

false
 alarm rate, 65
 negative rate. *see false alarm rate*
fast SVDD, 64
FastSLAM, 187, 195, 196, 223, 224,
 228
faults and failure detection, 63
FDI (Fault Detection Identification),
 243
F-distributed, 206
Feature
 Matching, 192

 space, 64, 65, 69-71, 73, 88
 vector, 67, 69-76, 79, 80, 82-84, 87,
 89, 90, 93-95, 97, 98, 100, 101
feedback, 36
final control elements, 246
First mode model, 331
Food processing, 265
Formal Methods (projects), 296
forward
 dynamics, 107
 kinematics, 144
 kinematics related to robot
 geometry, 111
 kinematics that relate to the
 velocities and accelerations, 111
FrameSLAM, 189
functional, 387-393, 396, 399, 400,
 424
Future
 aircraft systems, 265
Future and Emerging Technologies
 (FET), 249
fuzzy, 36
 adaptive control, 347
 adaptive control systems, 345
 landmarks, 208
 pose, 187, 190
 similarity, 208, 210
 systems, 346

G

Gabor
 filters, 67, 69
 texture measure, 67
gap-closing actuator
 GCA, 24
Gaussian kernel, 64, 92
gimballed gondola system, 106
Grow-When-Required neural network,
 61
gyroscopic gondola system, 139

H

H2020 (Horizon 2020), 233, 234,
 237, 244, 249, 251-254, 257, 258,
 268, 271, 276, 291-294, 300, 301,
 308, 310, 311
Hamiltonian, 389, 391-393, 395, 398
Hamiltonian function, 389

Hamilton-Jacobi equation, 424
 Hamilton-Jacobi-Bellman, 392, 396, 424
 Hessian Matrix, 205
 HJB equation, 392, 393, 396, 397, 399, 409, 412-417, 420
 homogenous matrix, 110
 HSV (Hue, Saturation, Value) color space, 68
 Hue, 68
 Human in the loop, 240
 human perceptual system, 66
 hybrid approach, 195, 196, 226

I

IEEE
 Control Society, 257
 Internet Society, 257
 IM minimal energy control, 396
 image, 61, 63-69, 71, 73, 75-77, 79-81, 83-98, 100
 image segmentation, 67
 importance sampling, 197
 indoor environment, 61, 66, 78
 induction motor, 409, 415
 Industry 4.0, 255
 Innovations squared mismatch (ISM), 326
 Integral Absolute Error, 367
 inverse dynamics, 144
 Inverse dynamics algorithm, 113
 inverted pendulum system, 373

J

jerk, 132
 Joint Undertakings, 237, 251, 271
 jounce, or snap, 124

K

Kalman observers, 324
K-dimensional space, 70
 kinematic, 37, 40, 41
 KLT, 202
k-means, 71, 92
 knowledge base, 66

L

L_1 -norm, 70, 75
 L_2 -norm, 70
 Lagrange multipliers, 389
 Laplacian, 202, 206
 Large Scale, 267
 Laser processing, 264
 leaf node, 72, 73, 76
 Library (Control), 266
 Linear
 parameter variable (LPV), 263
 velocities, 112, 142
 linkage, 19
 loop closure, 187, 189, 191, 194, 228

M

machine learning, 62, 66
 mammograms, 63
 Map Building, 212
 Mapping Projects, 235
 Marie Skłodowska-Curie Actions (MSCA), 250
 matrix on the inertia, 113
 Maximum a-posteriori probability (MAP), 324
 maximum likelihood, 195
 Maximum Likelihood Sequence Detection, 330
 MES (Manufacturing Execution System), 243
 Metacognitive Systems, 273
 metric, 62, 65, 73, 80
 micro fabrication technology, 17
 microrobot, 17, 18, 20, 23, 24, 29, 31, 32
 minimal energy control, 396, 398
 minimum
 pontryaguin, 392
 spanning tree (MST), 71, 79
 Minkowski power formula, 70
 Mixed criticality Systems, 265
 Mobile
 Manipulators, 36
 robotics, 63
 Model-checking, 301
 Modelling (Systems), 266
 MPC, 266

N

Nano-structure Control, 264
National R&D Programmes, 253
nearest neighbor search
 approximate nearest neighbor
 search, 61, 65, 71-76, 80, 90,
 101
neural network, 36, 62-64, 66, 82, 83,
 100
Newton-Euler
 equation, 115
 recursive method, 108
NIST, 258
nodes of a graph, 191
Nonholonomic, 36
nonlinear systems, 345
Non-linear Systems (projects), 292
nonparametric modeling, 62
normal (i.e., radial), tangential and
 vertical acceleration forces, 148
normal (radial), tangential and vertical
 acceleration force G components,
 119
normal acceleration, 105
normality, 62, 78
novelty
 novelty filter, 61-66, 73, 74, 76, 77,
 81-85, 88, 89, 91-93, 96, 97,
 100
NSF, 258

O

ODE (Ordinary Differential
 Equations), 241, 291
odometric link, 191
optimal
 control, 387-389, 393-397, 399, 401,
 404, 411, 413, 415, 418, 421, 424
 control problem, 387, 389, 393,
 394, 424
 control value, 395
 control variable, 397, 399, 413, 415
 lux, 410, 417, 418
 value, 392, 395
 VECTOR CONTROL, 420, 421,
 423
optimisation, 234, 239, 241, 243, 244,
 252, 259-268, 270, 272, 274, 275,
 304

Optimisation (Projects), 267
 problem, 387, 424
optimum trajectory, 413
outdoor environment, 61, 66
outlier, 202, 207

P

parametric modeling, 62
particle
 filters, 187, 189, 190, 196, 197, 228
 weight, 193, 195, 199
patch, 61, 65-69
PCBN Tool Wear, 178
 Mechanisms, 174
PDE (Partila Differential Equations),
 241, 305-308
PDEs, 305
penalty function, 396
perceptual learning, 61, 66
PID controllers (revisiting), 274
pitch angle of the SDT, 150
pixel, 67, 68, 74
point-to-point movements, 151
Pose error, 218
posterior distribution, 197, 198
power sources, 17
preimage, 64
principal moments of inertia, 113
Principle Component Analysis, 64
Proportional Integral (PI) controller,
 355

Q

quantization, 72

R

R&D space, 236
Rail Signaling, 265
RAMI (Reference Architecture-
 Industry 4.0), 270
Rao-Blackwellized, 189, 190
receptive field, 67, 69
Redundancy, 36, 41
Refactoring, 275
Refactoring Methods (Projects), 299
regression, 47, 48, 63
regressor, 43
relative entropy, 197

re-projection, 192, 195, 199
resolution, 67
RGB color space, 68
rigorous Systems-Control-
 Optimisation (SCO) methods, 261
robot vision system, 66, 78, 89
Robot's
 environment, 216
 path, 187, 190, 218
Robotics (platform, EU), 268
Robotics (projects), 309
robust, 37, 50, 58
 adaptive control, 353
 control, 264
roll angle of the SDT, 150
roll, pitch and yaw angular velocities,
 121
roll, pitch, and yaw angular velocity
 components, 106
root, 72
rotation, 67
rotor flux, 387, 400, 404, 409, 410,
 412-417, 420, 421, 424
RSLAM, 187, 189, 190, 195, 212,
 221-223, 227
Run Time Verification, 301

S

SAE J3016 (Standardisation), 240
safety, 265
Saturation, 68
SCADA (Supervisory Control & Data
 Aquisition System), 242
Scalable Vocabulary Tree (SVT), 71
SCO (Systems, Control,
 Optimisation), 234
score
 novelty score, 62
Self Organisation (projects), 314
self-organizing learning mechanism,
 63
Sensitivity (control systems), 263
sensor networks, 63
sensors, 247, 267
Sensors design, 265
servo errors, 125
shape memory alloy, 17, 18, 20
Si photovoltaic cells
 PV cells, 18, 31
SIFT, 201

silicon wafer, 18
similarity measure, 70, 72
simple cell
 V1 simple cell, 67, 69
Simulation, 267
sliding mode, 37
Smart Anytime Everywhere (SAE),
 254
sparse vector, 69
spatial disorientation trainer, 106
state
 variables, 387, 390, 391
 vector, 393, 394
stationary condition, 395
Stem Cells Systems (projects), 315
stereo pair, 187, 189, 201, 202
Super-Intelligence, 277
Super-Intelligence (views), 277
support vector data description, 61,
 64, 92
SURF, 188, 201, 202, 206, 208, 213,
 227
Symbolic Control, 308
symmetric, 39, 42, 45, 47
System(s) of Systems (SoS), 240
Systems Thinking, 241, 281, 295

T

tangential acceleration, 105
task space, 36, 38, 42, 43, 58
Taylor theorem, 394
Taylor's expansion, 411
Technology Readiness Level (TRL),
 251
Temporal Logic, 264
Testing, Standardisation &
 Certification, 267
threshold
 novelty threshold, 62, 65, 66, 73-
 76, 81-83, 86, 87, 89, 91, 93, 95,
 98-101
Tools (Software), 266
Topographic Labelling, 203, 216-218
Tracking, 36, 51, 55
traffic intersection, 88, 92
trajectory, 36, 50, 54, 187, 190, 217,
 219
Transient Regime, 387
transverse, lateral and longitudinal
 acceleration force components, 119

transverse, lateral and longitudinal
acceleration force G components,
106

U

Ultra Large-Scale Systems (ULSS),
241
uncertainties, 36, 38, 46-48, 50, 51,
53-55, 58
Underwater Vehicles, 253

V

Variable geometry thrusters, 264
VDMA, 257
vector control, 415, 416, 420, 422
Verification, 253, 274, 299
Verification (projects), 296

video, 61, 63, 65, 68, 71, 78, 79, 83,
89, 92, 93, 98, 101
video surveillance, 61, 63, 65
Virtualisation, 267
visual percept, 61
vocabulary
percept, 65
tree (VT), 65

W

wavelength, 69
weight function, 195, 196, 198, 199,
200
weighting factors, 393, 413
winner, 73, 82

X

xenon lamp, 26, 27

Advances in Robotics and Automatic Control: Reviews Volume 1

Sergey Y. Yurish, Editor

Industrial robots offer many benefits, including cost reduction, increased rate of operation and improving quality, along with improved manufacturing efficiency and flexibility. The demand for industrial robotics is majorly observed in industries such as automotive, electrical & electronics, chemical, rubber & plastics, machinery, metals, food & beverages, precision & optics, and others. In its turn, industrial automation control market will witness considerable growth during the same period with the growing demand of products such as sensors, drives and various robots.

The first volume of the *Advances in Robotics and Automatic Control: Reviews*, Book Series started by IFSA Publishing in 2018 contains ten chapters written by 32 contributors from 9 countries: Belgium, China, Germany, India, Ireland, Japan, Serbia, Tunisia and USA.

This book will be a valuable tool for those who involved in research and development of various robots and automatic control systems.

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