Mobile Intelligent Autonomous Systems

EDITED BY

Jitendra R. Raol • Ajith K. Gopal

CRC Press
Taylor & Francis Group

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
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CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
Version Date: 20120612

International Standard Book Number: 978-1-4398-6300-8 (Hardback)

Library of Congress Cataloging-in-Publication Data

Mobile intelligent autonomous systems / editors, Jitendra R. Raol, Ajith K. Gopal.
p. cm.
Summary: "Written for systems, mechanical, aero, electrical, civil, industrial, and robotics engineers, this book covers robotics from a theoretical and systems point of view, with an emphasis on the sensor modeling and data analysis aspects. With the novel infusion of NN-FL-GA paradigms for MIAS, this reference blends modeling, sensors, control, estimation, optimization, signal processing, and heuristic methods in MIAS/robotics, and includes examples and applications throughout. The organization of the book is based on fundamental concepts, with sections covering fundamental concepts, methods and approaches, block/flow diagrams, and numerical examples. A MATLAB-based approach is used through selected case studies in the text"-- Provided by publisher.
Includes bibliographical references and index.
ISBN 978-1-4398-6300-8 (hardback)
1. Intelligent control systems. 2. Motor vehicles--Automatic control. 3. Mobile robots. I. Raol, J. R. (Jitendra R.), 1947- II. Gopal, Ajith K.

TJ217.5.M63 2012
629.8'932--dc23 2012021068

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Mobile Intelligent Autonomous Systems

This book is dedicated
in loving memory to
Professor Dr. Naresh Kumar Sinha
(McMaster University, Hamilton, Ontario, Canada)
for his life-long contributions to Control Systems—Theory & Practice

Preface

Mobile Intelligent Autonomous System (MIAS) is a fast-emerging and developing research area. Although it can be regarded as a general R&D area, in the literature it is mainly directed towards robotics, field or other type of robots. However, for the purpose of the present volume the MIAS should not be and is not only considered to mean the field of robotics. The MIAS here is meant to comprise theory and practice of several closely related technologies that have some elements of mobility, intelligence and/or autonomy operating and envisaged not only for robots, but also for other mobile vehicles: (i) micro-mini air vehicles (MAVs) and (ii) unmanned aerial vehicles (UAVs). Several important subareas within MIAS research and development are: (a) perception and reasoning, (b) mobility, autonomy and navigation, (c) haptics and teleoperation, (d) image fusion/computer vision, (e) mathematical modelling of robots and their manipulators, (f) hardware/software architectures for planning and behaviour learning leading to robotic sophisticated architectures, (g) vehicle–robot path and motion planning and control and (h) human–machine interfaces for interaction between humans and robots and other vehicles. The application of artificial neural networks (ANNs), fuzzy logic/systems (FLS), probabilistic and approximate reasoning (PAR), static and dynamic Bayesian networks (SDBN) and genetic algorithms (GA) to many of the above-mentioned problems is gaining impetus. Multi-sensor data fusion (MSDF) also plays a very crucial role at many levels of the data fusion process: (i) kinematic fusion (position, bearing only tracking), (ii) image fusion and tracking (for scene recognition), (iii) information fusion (for building world models) and (iv) decision fusion (for tracking and control actions). MIAS area as a technology is very useful for automation of complex tasks, surveillance in hazardous and hostile environment, human assistance in very difficult manual works, medical and field robotics, hospital reception systems, auto-diagnostic systems and many other related civil and military systems including mining robotics. Many other significant research areas for MIAS consist of sensor and actuator modelling, sensor failure detection, management and reconfiguration, object-scene understanding, knowledge acquisition and representation, and learning and decision making. Examples of dynamic systems generally considered within the MIAS are: (a) autonomous systems [unmanned ground vehicles (UGVs), unmanned aerial vehicles (UAVs), micro and mini air vehicles (MAVs), autonomous underwater vehicles (UWVs)], (b) mobile and fixed but autonomous robotic systems, (c) dexterous manipulator robots, (d) mining robots, (e) surveillance systems and (f) networked and multi-robot systems.

This volume on MIAS deals with many of the above aspects and applications (not necessarily all) across 35 contributed chapters. Many chapters deal with the topics that span new research and development of very recent past—last 3–4 years. There are some good books on various aspects of robotics; however, the treatment of such aspects as outlined above is somewhat limited or highly specialized (sometimes it is too general). The treatment in this volume is comprehensive and covers several related disciplines which would help in understating the robotics and MIAS from system-theoretic as well as practical point-of-view. On the whole the editors feel that there is a fair representation of various aspects and current issues related to the MIAS in the sense of the term clarified in the beginning. The main idea is that several of the disciplines considered and discussed in this book would be needed to build a good autonomous and/or intelligent mobile system; however, the mechanical and structural aspects of the vehicles are not addressed in this book. Where possible, the authors of some of the chapters illustrate certain concepts and theories with examples via numerical simulations coded in MATLAB®. At the outset it is clearly stated here that neither the editors (of this book) nor the authors (of various chapters in the volume) claim that the mathematical expressions, equations and/or formulae presented in the book are derived from first principles. For such derivations the readers may refer the respective cited references in the concerned chapters. Also it is not claimed that all the chapters discuss all the aspects of mobility, autonomy and intelligence. None the same the volume as a whole discusses various conceptual foundations, MIAS and robotics systems, and allied technologies to MIAS and robotics. The end users of this integrated technology of MIAS/robotics (theory and practice) will be systems-control-educational institutions, several R&D laboratories, mechanics-aerospace and other industries, transportation and automation industry, medical- and mining-robotics development institutions and related industries.

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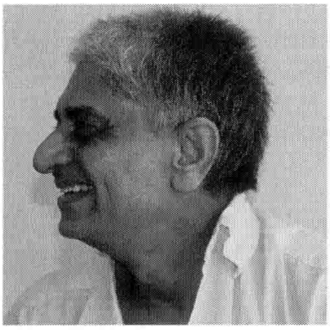
Web: www.mathworks.com

Acknowledgements

Several researchers and engineers all over the world have been making substantial contributions over the last four decades to this exciting and intriguing field which has caught the imagination of persons from all walks of life. It is emerging as an enabling technology to reckon with, especially for robotics, aerospace engineering and technological applications, and some industrial spin-offs. Certain interactions with the MIAS group of the CSIR (Council of Scientific and Industrial Research, in South Africa) and with a few colleagues of departments of electronics and communications engineering (E&CE), and instrumentation technology (IT) of M. S. Ramaiah Institute (MSRIT) have been very useful. The editor (J. R. Raol) is grateful to Dr. R. M. Jha (senior scientist, National Aerospace Laboratories (NAL), Bangalore) for his very useful initial tips a few years ago for publishing a book with international publishers, and continual guidance. He is also very grateful to Dr. Sethu S. Selvi (Head, E&CE), and Professor P. P. Venkat Ramaiah (Head, IT) for their moral support. He is especially very grateful to Ms. A. N. Myna (assistant professor, Information Science and Engineering, MSRIT) for her continual moral support during the writing of this book. The editors are very grateful to all the authors for their time, effort and patience and for ably contributing various chapters to this volume. We are also very grateful to CRC Press and especially to Mr. Jonathan Plant, Ms. Jennifer Ahringer, and Ms. Amber Donley for their full support during this book project. We are, as ever, very grateful to our spouses and children for their endurance, care, affection, patience, love and more—their additional spiritual presence in our lives and all that collectively inspires and gives us considerable strengths to go ahead in the midst of myriads of uncertainties and obstacles.

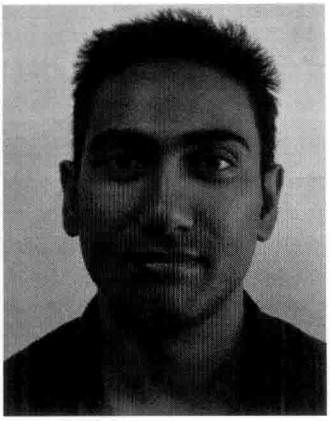
Jitendra R. Raol and Ajith K. Gopal

Editors



Jitendra R. Raol received B.E. and M.E. degrees in electrical engineering from M. S. University of Baroda, Vadodara, in 1971 and 1973, respectively, and a PhD (in electrical and computer engineering) from McMaster University, Hamilton, Canada, in 1986, where he was also a researcher and a teaching assistant. Dr. Raol taught for 2 years at the M. S. University of Baroda before joining the National Aeronautical Laboratory (NAL) in 1975. At NAL he was involved in the activities on human pilot modelling in fix- and motion-based research flight simulators. He re-joined NAL in 1986 and retired on 31 July 2007 as scientist-G (and head, Flight Mechanics and Control Division (FMCD) at NAL). He has visited Syria, Germany, the United Kingdom, Canada, China, the United States of America and South Africa on deputation/fellowships to work on research problems on system identification, neural networks, parameter estimation, multi-sensor data fusion and robotics, to present several technical papers at several international conferences, and deliver guest lectures at these places. He became Fellow of the IEE (United Kingdom) and a senior member of the IEEE (United States). He is a life-fellow of the Aeronautical Society of India and a life member of the System Society of India. In 1976, he won the K. F. Antia Memorial Prize of the Institution of Engineers (India) for his research paper on non-linear filtering. He was awarded a certificate of merit by the Institution of Engineers (India) for his paper on parameter estimation of unstable systems. He has received one best poster paper award for a paper on sensor data fusion and a gold medal and a certificate for a paper related to target tracking (from the Institute of Electronics and Telecommunications Engineers, India). He is also one of the recipients of the CSIR (Council of Scientific and Industrial Research, India) prestigious technology shield for 2003 for the contributions to the development of Integrated Flight Mechanics and Control Technology for Aerospace Vehicles in the country. The shield was associated with a plaque, a certificate and the prize equivalent of $67,000 for the project work.

Dr. Raol has published 110 research papers and several reports. He has guest-edited two special issues of Sadhana (an engineering journal published by the Indian Academy of Sciences, Bangalore) on advances in modelling, system identification and parameter estimation and on multi-source, multi-sensor information fusion. He has also guest-edited two special issues of the *Defense Science Journal* on MIAS and on aerospace avionics and allied technologies. He has guided six doctoral and eight master scholars and presently he is guiding six faculty members for their doctoral programmes. He has co-authored an IEE (UK) Control Series book, *Modeling and Parameter Estimation of Dynamic Systems* (2004), and a CRC Press (USA) book, *Flight Mechanics Modeling and Analysis* (2008). He has also authored a CRC Press book, *Multi-sensor Data Fusion with MATLAB* (2009). He has served as a member/chairman of several advisory, technical project review and doctoral examination committees. He is reviewer of several national and international journals. He is on the board of directors of a private R&D company as well as a private college in the state. His main research interests have been data fusion, system identification, state/parameter estimation, flight mechanics–flight data analysis, H-infinity filtering, ANNs, fuzzy systems, genetic algorithms and robotics. He has also authored *Poetry of Life* (Trafford Publishing, USA, 2009) and *Sandy Bonds* (Pothi.com, India, 2010) as the collection of his 140 poems.



Ajith K. Gopal qualified with a B.Sc. Eng. (Mechanical) from the University of Natal in South Africa in 1997. He subsequently completed the M.Sc. Eng. in 2000 in structural analysis of composite material and in 2003 obtained a PhD in engineering, from the University of Natal, for his work in energy absorption of smart materials. Dr. Gopal has 12 years of working experience, of which 8 years has been in the research and development domain. He is responsible for establishing the MIAS (Mobile, Intelligent, Autonomous Systems) research group at the CSIR in South Africa, in 2007, where he served as the research leader for 2007 and 2008.

Dr. Gopal has published four papers relating to composite and smart materials in the *Journal of Composite Materials* published by Elsevier and at *International Conferences on Composite Science and Technology*. He has also published a paper on path planning in the *Defense Science Journal*, a book chapter on data fusion in robotics in the CRC Press book *Multisensor Data Fusion with MATALB* (by J. R. Raol, 2010) and guest-edited a special issue of the *Defense Science Journal* on MIAS. He is currently an engineering/project manager at Land Systems South Africa where he is responsible for new technology strategy and development for the company.

Contributors

C. M. Ananda
ALD-Aerospace Electronics and Systems Division
CSIR-National Aerospace Laboratories
Bangalore, India

N. Ananthkrishnan
Independent Consultant
Mumbai, India

R. Ayyagari
Department of Instrumentation and Control Engineering
National Institute of Technology
Tiruchirappalli, India

Antoine Bagula
Department of Computer Science
University of Cape Town
Cape Town, South Africa

Victor M. Becerra
School of Systems Engineering
University of Reading
Reading, United Kingdom

Niteen Bhange
Coral Digital Technologies (P) Ltd.
Bangalore, India

Seetharama M. Bhat
Department of Aerospace Engineering
Indian Institute of Science
Bangalore, India

Dimitar Chakarov
Department of Mechanics and Multibody Systems
Institute of Mechanics
Bulgarian Academy of Sciences
Sofia, Bulgaria

Charu Chawla
Department of Aerospace Engineering
Indian Institute of Science
Bangalore, India

Jong Ho Choi
Industry University Collaboration Foundation
Chungnam National University
Daejeon, Korea

Julia H. Downes
School of Systems Engineering
University of Reading
Reading, United Kingdom

Ajith K. Gopal
Land Systems South Africa
Johannesburg, South Africa

Girija Gopalratnam
Flight Mechanics and Controls Division
CSIR-National Aerospace Laboratories
Bangalore, India

Nitin K. Gupta
IDeA Research and Development (P) Ltd.
Pune, India

Rong Haijun
Xi'an Jiaotong University
People's Republic of China

Mark W. Hammond
School of Systems Engineering
University of Reading
Reading, United Kingdom

R. M. Jha
Aerospace Electronics and Systems Division
CSIR-National Aerospace Laboratories
Bangalore, India

M. R. Kaimal
Department of Computer Science and Engineering
Amrita Viswha Vidyapeetham University
Kollam, India

C. Kamali
Flight Mechanics and Control Division
National Aerospace Laboratories
Bangalore, India

Kostadin Kostadinov
Department of Mechanics and Multibody Systems
Institute of Mechanics
Bulgarian Academy of Sciences
Sofia, Bulgaria

Marelize Kriel
CSIR Defence, Peace, Safety & Security
Pretoria, South Africa

Louise Leenen
Information Systems Research Group
Council of Scientific and Industrial Research
Pretoria, South Africa

Venkatesh K. Madyastha
Flight Mechanics and Controls Division
CSIR-National Aerospace Laboratories
Bangalore, India

Simon Marshall
School of Chemistry, Food Biosciences and Pharmacy
University of Reading
Reading, United Kingdom

M. Meenakshi
Department of Information Technology
Dr. Ambedkar Institute of Technology
Bangalore, India

A. N. Myna
Department of Information Science and Engineering
M. S. Ramaiah Institute of Technology
Bangalore, India

V. P. S. Naidu
Flight Mechanics and Control Division
CSIR-National Aerospace Laboratories
Bangalore, India

Slawomir J. Nasuto
School of Systems Engineering
University of Reading
Reading, United Kingdom

Isaac O. Osunmakinde
School of Computing
College of Science, Engineering and Technology
University of South Africa (UNISA)
Johannesburg, South Africa

Radhakant Padhi
Department of Aerospace Engineering
Indian Institute of Science
Bangalore, India

Ik Soo Park
Industry University Collaboration Foundation
Chungnam National University
Daejeon, Korea

Abhay A. Pashilkar
Flight Mechanics and Control Division
CSIR-National Aerospace Laboratories
Bangalore, India

Ambalal V. Patel
Integrated Flight Control Systems Directorate
Aeronautical Development Agency
Bangalore, India

A. Ramachandran
Department of Instrumentation Technology
M. S. Ramaiah Institute of Technology
Bangalore, India

Jitendra R. Raol
Department of Electronics and Communications Engineering
M.S. Ramaiah Institute of Technology
Bangalore, India

Vishal C. Ravindra
Flight Mechanics and Controls Division
CSIR-National Aerospace Laboratories
Bangalore, India

Herman le Roux
CSIR Defence Peace Security and Safety
Council of Scientific and Industrial Research
Pretoria, South Africa

Shobha R. Savanur
Department of Electrical Engineering
P. G. Halakatti College of Engineering and Technology
Bijapur, India

Motlatsi Seotsanyana
Mobile Intelligent Autonomous Systems Group
Council for Scientific and Industrial Research
Pretoria, South Africa

S. Seshadhri
Industrial Software Systems
ABB Corporate Research
Bangalore, India

Hema Singh
Aerospace Electronics and Systems Division
CSIR-National Aerospace Laboratories
Bangalore, India

G. K. Singh
Flight Mechanics and Control Division
CSIR-National Aerospace Laboratories
Bangalore, India

N. Sundararajan
School of Electrical and Electronic Engineering
Nanyang Technological University
Singapore

Alexander Terlunen
Department of Information Technology
University of Pretoria
Pretoria, South Africa

Bhekisipho Twala
Department of Electrical and Electronic Engineering Science
University of Johannesburg
Johannesburg, South Africa

R. Vrinthavani
Center for Airborne Systems
Defence Research and Development Organisation
Hyderabad, India

Rahee Walambe
Coral Digital Technologies (P) Ltd.
Bangalore, India
and
Department of Engineering
Lancaster University
Lancaster, United Kingdom

Kevin Warwick
Department of Cybernetics
University of Reading
Reading, United Kingdom

Benjamin J. Whalley
School of Chemistry, Food Biosciences and Pharmacy
University of Reading
Reading, United Kingdom

Dimitris Xydas
School of Systems Engineering
University of Reading
Reading, United Kingdom

Chika O. Yinka-Banjo
Department of Computer Science
University of Cape Town
Rondebosch, Cape Town, South Africa

Hyun Gull Yoon
Industry University Collaboration Foundation
Chungnam National University
Daejeon, Korea

Introduction

Jitendra R. Raol and Ajith K. Gopal

Over the last two decades, there has been considerable advancement of various technologies applicable to mobile vehicles, in general, and robots, in particular. Since it would be a formidable task to keep track of this technological progress, only a small and humble attempt has been made to present in this volume on MIAS, descriptions of some of the most important aspects of robotics and some recent progress not only in the field of robotics but also in the field of other types of mobile vehicles.

At the outset, a robot as a vehicle (either static or dynamic depending upon the intended purpose of its use) is defined variously by various people and/or groups [1] as: (i) 'an automatically controlled, reprogrammable, multi-purpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications' (by the International Organization for Standardization [ISO 8373] and International Federation of Robotics [IFR]) and (ii) 'a reprogrammable multi-functional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks' (by Robotics Institute of America [RIA]). However, Joseph Engelberger, the inventor of the first industrial robot in history says, 'I can't define a robot, but I know one when I see one'. An intelligent robot can be considered as machine or system that has an ability to extract information that it requires from its own environment and then use this information to plan its paths and trajectory so that it can move in its surroundings avoiding the obstacles in a purposeful manner. It can also be visualized as a system that autonomously senses it own environment and then acts in that surrounding. The so-called smart sensors also have similar abilities. Autonomous robot/vehicle will have an ability to make its own decisions and then take necessary action to execute a given task. This autonomy gives a robot the ability to sense its own situation and then act on it so that any task is executed with minimal or no intervention from any human operator. The full autonomy is in an autonomous robot/vehicles and a partial autonomy is in, say, teleoperated robots.

From the above definitions of a robot, the important aspects that emerge are handling or dealing with: (i) manipulator, (ii) several axes system, (iii) industrial automation, (iv) programmed motions, or un-programmed but behavioural motions and (v) autonomy. The manipulator implies that a robot is used as an extension of a human arm to carry out difficult manual or hazardous tasks. This extended arm would be stronger and longer (or even shorter) than the normal human arm, flexibility not being ruled out. The arm would move relative to the body of the robot where it is attached. The manipulator should be controllable and this will add to the number of degrees of freedom (DoF) beyond the basic coordinates of the robot movements (6DoF). Thus, the DoF in case of a robot might be more than six. An industrial robot is supposed to help in mundane industrial tasks of movement of objects, lifting of tiny or big mechanical parts, and handling assembly line works. It is most likely that many or most robots would be controlled or guided and navigated by some programmed commands (for initiating and continuing the motions), these being done remotely (by teleoperation) or from the onboard computers of the robots. Many of these activities are also common for other mobile vehicles, like mini-micro-air vehicles (MAVs), and to some extent to the unmanned aerial vehicles (UAVs) and/or underwater autonomous vehicles (UWAVs). Many unmanned ground vehicles (UGVs) also would have similar or some advanced features of programmed actions and resultant motions. So, from an immediate perspective and in a nutshell a robot is a mechanical device that performs various tasks. It could be controlled by a human being or is an autonomous mobile machine. However, since a robot is called upon to perform variety of tasks it would be equipped with sensors (cameras, acoustic devices, IR sensors), will have onboard computers on/in its body, and will have wires and cables (electrical or otherwise) connecting various subsystems. Hence, a robot can be visualized as a composite system that would mostly be a mechatronic system rather than only a mechanical system. Thus, a robot has basically a mechanical system, an electrical power supply (battery cells-) system, (vision, acoustic, EM-) sensors, actuators, onboard computers (or micro-processor-controller systems), data processing (algorithms) systems and control systems to command, guide and carry out movements of the mobile vehicle. Hence, such a system is an electro-mechanical (or even electro-hydraulic/pneumatic) system. The mechanical system of a general robot would comprise of the chassis, motors and wheels, the latter for the wheeled robots. The wheeled robot might have a drive of the type of a car, skid steer, differential drive, synchronous or pivot drive. Most robotic systems are powered by a set of batteries. The robots actuators convert electrical energy to mechanical energy/work which might be either rotational/angular (obtained by using electrical motors) or linear motion (obtained by using electromagnetic devices). These motors could be of various types: (a) AC (alternating current), (b) DC (direct current), (c) stepper motors and (d) servo motors; the latter are DC motors with some feedback capability and error compensation. In most robotic systems DC, stepper or servo motors are used.

We can visualize from the foregoing that the field of robotics, in a broader sense, encompasses the following disciplines: (i) sense, (ii) think and (iii) act. These three processes are equally applicable to other autonomous mobile vehicles. For example, a micro-air vehicle can be considered as a micro-air robot carrying out a specified task of monitoring an area for security reasons. The sensing involves measuring devices, and processing of the measured data; these data could be in the form of images and/or kinematic (position, etc.). These data are filtered using Kalman filters or even some advanced filtering techniques: derivative-free Kalman filter, particle filter or information filter. For real-time/online data processing one needs to resort to some simpler, computationally efficient and numerically stable filtering approaches. Some sensors would have in-built data processing units/facilities, the smart sensors. Examples of sensors are LIDAR (light detection and ranging), GPS (global positioning system), IMU (inertial measurement unit), Sonar (sound navigation and ranging), IR (Infra Red) camera and so on. These sensors give information of the obstacles in the path of the robot and/or the landmark locations, in addition to the robot's own locations. Some combination of these measured data would be utilized to obtain more accurate information about the sensed object, obstacles or environment. This calls for the study and use of multi-sensor data fusion (MSDF) and associated methods [2]. The images of the tracked objects and landmarks are required to be processed in image/vision processing algorithms (and image fusion algorithms) and used for further decision making. The tracking of the images might also be required. The MSDF can be accomplished at the sensor level/data level or at the data processing level in filtering algorithms. To handle complex and sophisticated tasks and movements we need to have smart sensors, specialized sensors with low-power consumptions and even low-cost sensors. The smart sensors perform certain data pre-processing tasks that are anyway routinely required before carrying out further data fusion operations and processing. A robot exists in its own perceptual space, despite the fact that its own 'perception' capability might be limited compared to that of the human. Thus, the robot's state space is both: its internal state and its external state. The robot's state of perception can be enhanced using some elements of artificial intelligence (AI).

In terms of robot path planning (the task that can be divided amongst the 'sense' part and the 'think' part, because often the path planning is very intimately based on the sensed environment) and data filtering we need to move from classical and conventional algorithms to the ones based on soft computing and ones that combine features of the classical (and hence proven) and the new algorithms to derive benefits from both methodologies. The robot needs to 'think' to decide on what actions to take by itself for its further motion to carry out a specified task. This capability is divided into five sub-category tasks: (a) path-motion/trajectory planning, (b) autonomy (either 'thinking' is pre-wired or being done online in real time while executing the task), (c) kinematics/dynamics, (d) perception ('intelligent sensing') and (e) localization (could include mapping also). For a robot to move from its initial location to its goal point it needs to know what path to follow and how to follow the chosen path. Much of the assigned tasks need to be carried out by the robot automatically. The knowledge of the robot's kinematics as well as the robot's motion model (mathematical modelling) is very important for successful robotic actions. These mathematical models are also needed to carry out simulation of robot's behaviour and its intended operations. This simulation helps designer in optimizing the robotic sub-systems (sensor and control management) to achieve a desired goal with certain specifications/accuracy and so on. That an autonomous mobile system needs to be equipped with 'perception' is very important for accurate path/motion planning, simultaneous localization and mapping, and accurate and logical decision making. The major difference in a human system (human being) and a robot is the lack of perception capability in a robot/mobile vehicle. Perception is built up by sensing and interpreting the environment, understanding the importance of the task to be carried out, learning from previous experience, and adapting to the new situations, hitherto not encountered by a robot. For any man-made system this is a formidable task indeed. The final task is that of action. This involves the driving mechanisms, motion control and even biometric (human type) motion management. Generally, the concepts adopted are based on wheeled, tracked and bipedal robots, but we need to evolve the robots that increasingly use the concepts of biometric movements like the smooth reptilian movements. The robot uses the actuators (also called effecters) to carry out its actions. Due to the differences in the types of actuations the robots are categorized as either mobile, manipulator or communication robots.

The main difference between the human and a robot is that the human brain interprets the sensed data ('sense'), derives from these data the required information for decision making ('think') and directs ('act') the human organs to execute certain tasks automatically. The idea of AI is then to build computer systems/software/algorithms/processes to mimic the human brain's capability of thinking and action. Thus, AI has a great scope in the field of robotics and other mobile vehicles. The robot applications are: (i) industrial robots, (ii) medical/surgical robots, (iii) mining/trucks robots, (iv) humanoid robots, (v) farming tractor, (vi) MARS Rover, (vii) games/sports robots and (ix) unmanned aerial/ground vehicles. The unmanned aerial vehicles/robots are used in military, aerospace applications, mining, health care and even in teaching/training. The so-called foraging/rummaging robots are useful for (a) collecting samples from chemically hazardous places, (b) extraction of landmine, (c) exploring unknown regions, (d) collecting samples of rocks from other planets and (e) assembling parts on a manufacturing line. There are other uses of robotic systems: (i) an automatic mobile sweeper and (ii) an automatic car for children. The research in robotics and closely related fields (UAVs, MAVs, UGVs) encompasses several disciplines and technologies and their integration: (i) mechanical design, manipulators and actuation, (ii) mathematical modelling of robotic system (and other vehicles), including its environment, (iii) sensors, instrumentation and acquisition systems for measurements, (iv) pre-processing of measured data, filtering and data fusion, (v) image acquisition/fusion, processing and tracking, (vi) path and motion planning and algorithms to achieve optimal paths, (vii) algorithms for simultaneous localization and mapping, (viii) implementation of these and other algorithms onboard computers (micro-processors, embedded systems), (ix) implementation of sensor/actuator fault detection/management and reconfiguration schemes, (x) use of soft computing techniques for learning, adapting and decision making, (xi) guidance and navigation algorithms, (xii) multi-robot coordination mechanisms, and associated algorithms, (xiii) real time/online system identification and parameter estimation [3,4] for mathematical modelling of these mobile vehicles, (xiv) control algorithms and robotic systems' performance evaluation methods and (xv) hardware/software robotic architectural aspects for optimal configuration of the robotic system.

This volume covers many of the areas and disciplines mentioned above across 35 chapters contributed by experts from various fields and countries. Although each chapter can be read and studied independently, they are grouped into three logical parts to facilitate nearly smooth information flow throughout the book: Part I: Conceptual Foundations for MIAS, Part II: MIAS and Robotics and Part III: Allied Technologies for MIAS/Robotics. Many of the chapters attempt to present some new results in the form of novel techniques, algorithms and/or experimental/simulations/empirical data-analysis results, and other chapters either describe, in brief, the basic methods, technologies and/or review some literature in the relevant fields. Thus, the structure of this volume is a mixed one: it can be used as a recipe book, or a reference volume with some new results (like ones in a research/technical journal). It is not meant to be a text book for any course or syllabus however it can be used as a supporting volume and can be consulted for research projects at the post graduate as well as doctoral levels. At the outset it must be mentioned that neither the editors (of this volume) nor the authors (of various chapters in the volume) claim that the mathematical expressions, equations and/or formulae are derived from the first principles. For such derivations the readers can refer the respective cited references of the concerned chapters. Also, it is not claimed that all the chapters discuss all the aspects of mobility, autonomy and intelligent, nonetheless the volume as a whole discusses several basic concepts, MIAS and robotics systems, and allied technologies that would aid MIAS and robotics. The main idea is that the disciplines considered and discussed in this volume would be needed to build a good autonomous and/or intelligent mobile system, only that the mechanical and structural aspects of the vehicles are not addressed in this book. It must also be mentioned that the authors of various chapters seem to have taken enough care to present various theories, formulae/equations, simulations/real-data results and experimental results, it is important that the readers and users of this material, inferences, and results take enough care and precautions before applications of these to their own problems, case studies and systems. Any such endeavours would be at their own risk. Next, only a brief description of each chapter is given here for two reasons: (i) the importance of each work and related technology is clearly highlighted by the authors in the introductions of their chapters and (ii) the table of contents gives a good picture of what is being presented in the concerned chapters. The synergism connection diagram for the MIAS/Robotic System's theory and practice as presented in various chapters (whose numbers are indicated within parentheses) in this book is depicted in Figure I.1. Many of these technologies are the constituents to build a MIAS system, except that the mechanical structures and related aspects are not dealt with in this book.

In Chapter 1, some basic concepts of artificial neural networks, fuzzy logic and genetic algorithms are discussed. The scope of applications of these soft computing techniques as well as of AI to the robotic and other related systems is discussed. Also, certain combinations of ANNs, FL and GAs are described that are/can be used for robotic applications.

Chapter 2 by Ramachandran discusses mathematical modelling aspects for robot motion. Especially kinematics, dynamics, robot walking and probabilistic robot modelling based on available odometry measurements are considered.

In Chapter 3, Gopal discusses the need of data fusion in robotics. The author highlights the data fusion approaches and gives partial coding of these methods. The presentation is concise, but the importance of the data fusion applications to robots/MIAS should not be underestimated. Further aspects and application of multi-sensor data fusion are developed in Chapters 4, 5 and 30. In Chapter 4, Myna discusses image registration and fusion aspects. Some aspects of satellite image registration and fusion are presented with real imagery data. A good literature review of image registration is also provided. The concepts fuzzy logic type I and type II are highlighted for use in image fusion. Chapter 5 by Naidu presents discrete cosine transform-based method for image fusion. Also the performance evaluation results are presented using the image data from the open literature. In Chapter 6, Kaimal and the coauthor present a novel and improved motion segmentation process in the spectral framework. Specifically, they discuss motion detection, motion estimation clustering using spectral framework. The maximum likelihood motion framework is used. Extensive performance results of the approach are also presented.

In Chapter 7, the authors present some new work on formation control in multi-agent systems over packet dropping link. Since, data losses do occur in communications channels, be it the data transmission networks, multi-robot coordination data-networks, multi-target communications channels and/or wireless sensor networks, it is important to address this problem here.