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A review of mechatronics and bio-inspired mechatronics system

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Abstract

The increasing integration of combining with the hardware (the basic mechanism, electronic circuit board, transducer and actuator) and the software (information processing and overall control) results in integrated systems called mechatronic systems. The development progresses of a mechatronic system involve properly disposing every component for desired function. The progress has a very large influence on a variety of commercial products in the field of advanced robotic systems, Micro/Nanomechatronics, biomechatronics and healthcare, automotive systems, and so on. Indeed, the design concepts usually originate from the biological inspiration. By observing and inspiring the biological phenomena, behavior and similar structures, the correlative principles can be derived or understood and use them to help solve a non-biological problem. In the beginning, this paper enumerates some definitions for mechatronics engineering, and reviews the development history in the field of mechatronic systems. Secondly, the required components, key functions and eminent applications are discussed. In section two, the problems met in the progress from design to realization are proposed, such as biological inspiration and integration aspects. Next, the development of key components for mechatronic system is then described. Numerous literatures have been cited to emphasize the significance of mechatronic applications. Finally, the expectations and future perspectives of mechatronic systems are addressed.

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1. Introduction

Mechatronics is the integrated technologies that synthesize several evolving engineering disciplines and technologies including precision mechanical engineering, electrical engineering and computer science, control algorithm and systems thinking in the design of products and manufacturing processes. 3C (Computer, Communications, Consumer-Electronics) productions, automobile, household appliances, railways and vehicles are all examples of mechatronic systems. Mechatronics relates to the intelligent electromechanical products and how to design and manufacture. Mechatronics will cover a wide range of application areas including most of all electronic devices, for example, consumer product, instrumentation, automobile industry, machine tool industry, computer industry, aerospace industry, medical industry, robot industry, and so on.

A generalized definition of mechatronics is described as encompassed mechanical components and electronically based decision making (control circuitry). But, systems engineers consider that mechatronics is a form of concurrent design and manufacturing engineering practices (Hunt, 1988; Buur, 1990; Keys, 1991). Another definitions excerpted from literatures showed as following:

"Mechatronics is defined as the field of study involving the analysis, design, synthesis, and selection of systems that combine electronic and mechanical components with modern controls and microprocessors (Alciatore and Histand, 2005).

"Mechatronics is the synergistic combination of precision mechanical engineering, electronics, control engineering, and computer science (Craig and Stolfi, 1994)."

"Mechatronics is the application of complex decision making to the operation of physical systems (Auslander and Kempf, 1996)."

"Mechatronics is an engineering process that involves the design and manufacture of intelligent products or systems involving hybrid mechanical and electronic functions (Hsu et al., 1995; Hsu, 1998)."

People often mistakenly regard mechatronics as synonyms to "electromechanics." An electromechanical device such as a motor is usual in an electric system, but it isn't a mechatronic system. Mechatronic systems involve intelligent progress control related to mechanical engineering disciplines like mechanical dynamics, thermodynamic, and fluid dynamics. Most of all mechatronic systems require the capability of sensing the change of the real-world environment for intelligent control. In the other word, the various sensors assist mechatronic systems in achieving desired actions of a mechanical component, or the technological restrictions required in a specific manufacturing process. Often, researchers are required to apply various sensing technologies in addition to electromechanical principles. Therefore, to view a "Mechatronic system" as an "intelligent electromechanical system" is thus appropriate.

Mechatronics is a multidisciplinary engineering science, that involves three major disciplines of mechanical, electrical, and computer engineering, as shown in Fig. 1

A. Mechanical Engineering (machines, mechanical elements, dynamics and kinetics);

B. Electronic Engineering (microelectronics, power electronics, instrumentation, signal processing);

C. Computer Engineering (operation system, control theory, software engineering, artificial intelligence).

During the design processes of mechatronic systems, the interplay for the design in mechanical system and electronic system are crucial, and result in the simultaneous engineering has to be employed to achieve the goal of designing an overall integrated system and creating synergetic effects. In future, more sophisticated control algorithms will be realized, e.g., the estimation of non-measurable variables, the self-tune and adaptation of controller parameters, reconfiguration, supervision and fault diagnosis, safety and fault tolerance. Hence, the mechatronic systems with adaptive or even learning behavior can also be genuinely called intelligent mechatronic systems (Isermann, 2008).

Mechatronic technology brings out several improvements, for example, more system performance, higher product qualitative, cost-down of manufacture, lower power consumption, higher precision, efficiently transformation between electrical power and mechanical power, and so on (Hewit and King, 1996).

Mechatronics is a key cornerstone of modern industrial technologies, and it is developed toward more efficient, more convenient, more intelligent, more integrated and human-friendly.

1.1. Primitive mechatronic system

Technological history indicates that there has been a striving for improvement in mechatronic systems. The application fields of primitive mechatronic system highlight the marvelous ingenuity of their inventors, e.g., automotive mechatronics, manufacture equipment, industrial robot, household appliances, entertainment device. In the 19th century, the purely mechanical systems, also called premechatronic system, that decision making (computation) is done in the same medium as the major power flows in the system, and the control mechanism operate without electrical, hydraulic or pneumatic auxiliary energy. There are several oft-quoted examples, e.g., steam engine, typewriter, mechanical adding machine, pneumatic process controller, carburetor, sewing machine, tracer lathe, cam grinder (Auslander, 1996).

Due to the electronics technique develops year by year, there has always been striving for complexity and significant progress in mechanical systems. The technological development progress from the purely mechanical systems to mechatronic systems are shows in Fig. 1. (Isermann, 2008).

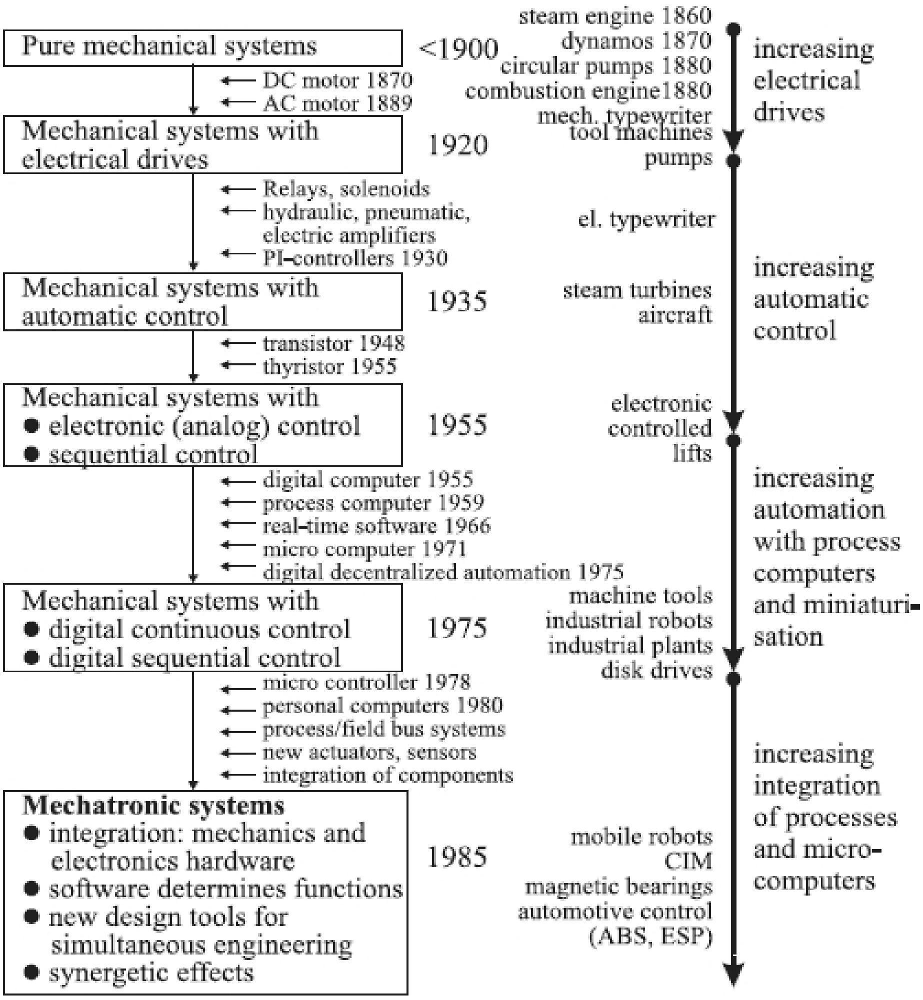


Fig. 1. Historical development of mechanical, electronic and mechatronic systems (Isermann, 2008).

1.2. Components and functions

A mechatronic system organization including central processing unit, actuator, instrumentation, controlled target system, operation interface and other elements, e.g., communication unit, power supply unit, tiny operation system, etc. The most common type of central processing unit in use today is the microcontroller that is very small, highly integrated microprocessors used as decision-making elements in mechatronic systems. The actuator is capable of controlling power delivery to achieve desired actions of a mechanical component. The instrumentation acquires the variation of controlled target system, and then feedbacks to microcontroller. A diagram of controlled mechatronic system with four central components was showed as Fig. 2.

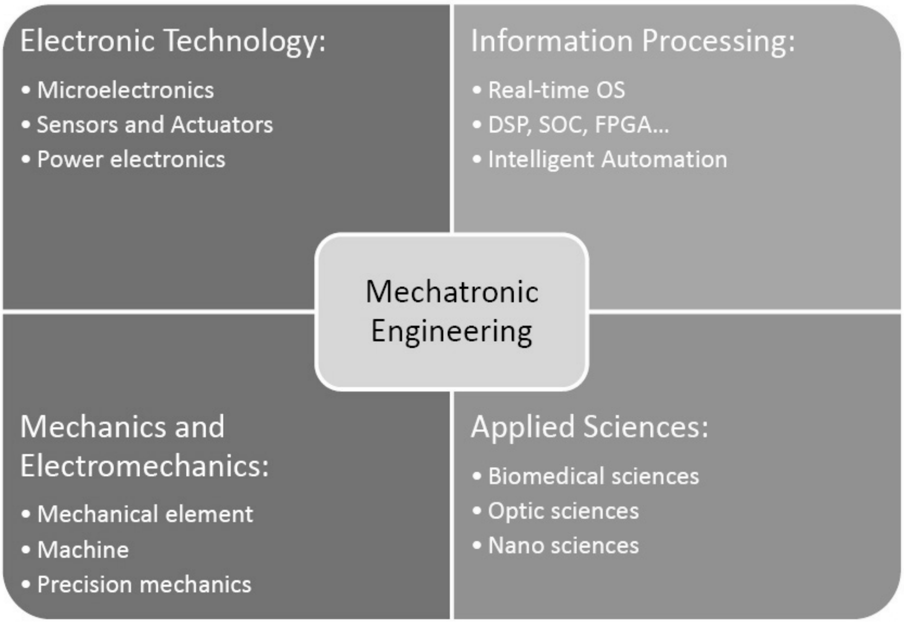


Fig. 2. Mechatronics: synergetic integration of different disciplines.

Basically, the major function in mechatronic system is the capability of sensing the change of the real-world environment to assist mechatronic systems in achieving desired actions of a mechanical component, or the technological restrictions required in a specific manufacturing process. Modern mechatronic system presents many improved and smart functions, e.g., the estimation of non-measurable variables, the self-tune and adaptation of controller parameters, reconfiguration, supervision and fault diagnosis, safety and fault tolerance. In the future, many autonomic functions including reconfigurability, self-organization, self-repair, autonomous evolution, and self-replication, and so on, will be implemented (Bekey, 2005).

1.3 Applications

The rapid development of mechatronic technologies result from ingenious mechanical engineering and marvelous electrical engineering in the past 20 years, and is applied to various industry to then develop a great deal of applications. According to their construction, traditional classification and industrial branches, these applications, so-called mechatronic industry, can be subdivided into Advanced robotic systems, Micro/Nanomechatronics, Medical mechatronics (Biomechatronics) and healthcare, Mechatronics in automotive systems, Opto-mechatronics, 3C products, Haptic devices and applications, Industrial manufacture, Space science, and so on. The development up until now can be found in Fig. 3 and literatures (Isermann, 2008).

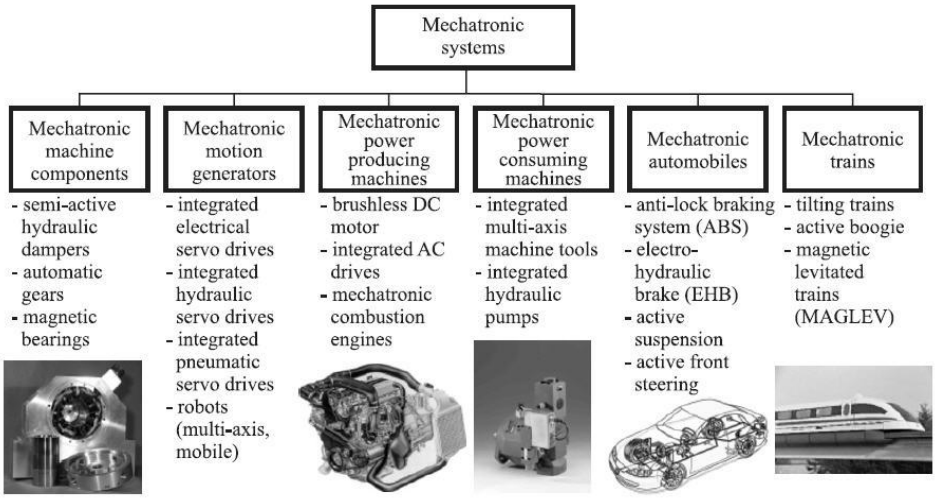


Fig. 3. Examples for mechatronic systems (Isermann, 2008).

2. Design philosophies in mechatronics engineering

Today, many mechatronic products are highly complex and often frangible. Although they have high degrees capability to serve their owner, many of systems are often incur catastrophic failure, difficult to maintain, and full of vulnerabilities to outside attack.

The important goal of optimum design is to be able to build systems that are more intelligent, more autonomous, and more robust in handling data in noiseful environment. Furthermore, they have the capabilities of self-configure automatically, self-reconfigure when components are damaged or destroyed, autonomic learn with minimal human intervention, and autonomic evolvement to improve what they are supposed to do.

2.1. Biological inspiration

In the previous decade, the move towards emulating nature and mimicking the wonders uncovered in biology resulted in biologically inspired systems. By observing and inspiring the biological phenomena, the correlative principles can be derived or understood and use them to help solve a non-biological problem. There are some observed aspects of the ways in which animals regulate their internal environments and control their movements in the world. These control and regulation methods were compared and contrasted with those used in engineering control systems, and inspired researchers to devise a framework for the design of intelligent controllers. Excellent results have been proposed in a wide range of scientific domains, that researchers inspired by nature enabling exploration, communication, and advances that were never dreamed possible just a few years ago.

Biological inspiration can play many different roles in mechatronics, and confusion about this multiplicity of meanings accounts for a wide spectrum of belief about the value of biology for developing better mechatronic systems and improved performance. One of most important roles is that it can serve as an existence proof of performance, that some desirable behavior is possible. On the other hand, it must be understood that a biological metaphor is applicable and relevant to a mechatronic problem, this does not mean that the corresponding biological phenomena can necessarily be understood in mechatronic terms.

For innovation or creations, a deeper understanding of biological phenomena is required, and there are at least three additional potential roles have been proposed: (Wooley and Lin, 2001)

A. Biology as source of principles, e.g., several well-known cases are artificial neural network, fuzzy logic, genetic algorithm, expert system, and so on.

B. Biology as implementer of mechanism, e.g., a variety of mobile robots including wheeled robots, legged robots (with two, four, six, and eight legs), flying robots, underwater robots, snakelike robots, climbing robots, jumping robots, and other kinds of robots.

C. Biology as physical substrate for mechatronics, e.g., some bioimechatronic system, medical mechatronics, auxiliary mechanism for disabled human, and so on.

2.2. From design to realization

A systemic progress and several modern software design tools are required during the design of mechatronic system. The mechatronic design is an iterative and integrated procedure, which involves several traditional domain specific engineering, e.g., mechanical, electrical/electronic, software, information, automation, user interface, and integrates multidisciplinary software and hardware environments for successful design, testing, prototyping, implementation and validation. The design aspects, such as requirements, environment, system of objectives, application scenarios, functions, active structure, shape and behavior, should be considered. And the important design steps included the distribution of interdisciplinary task, the use of sensors and actuators, the electronic, architecture, the software architecture, the controller design and the creation of synergies, resulting in totally desired functions. The development scheme is represented in form of a ‘‘V’’-model, which distinguishes especially between the mechatronic system design and system integration, as showed in Fig. 4. (VDI 2206; Isermann, 2008)

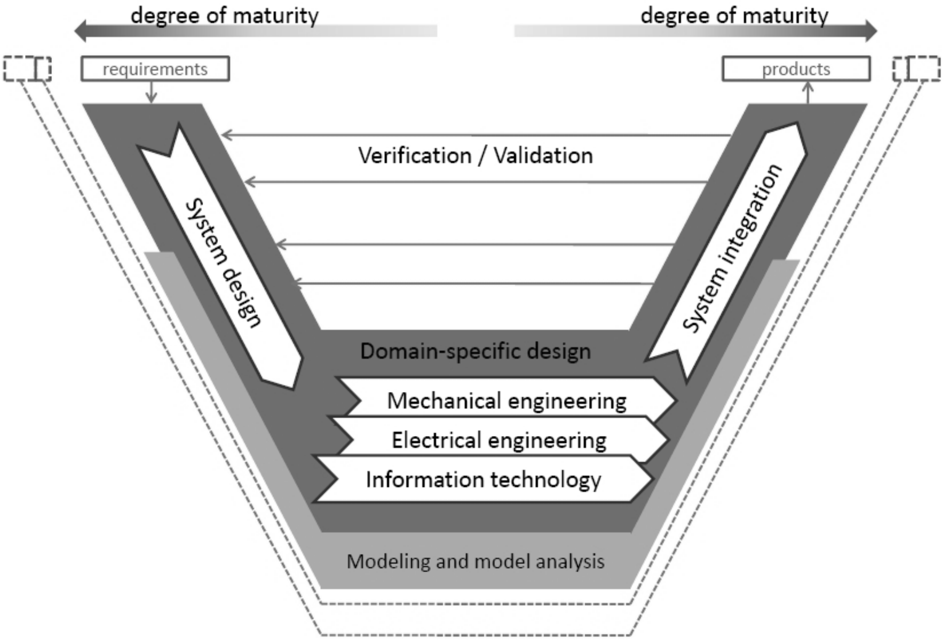


Fig. 4. V-model-development scheme for mechatronic systems.

2.3. Integration aspects

A mechatronic system refers to a synergistic combination of interdisciplinary tasks, including mechanical, electrical/electronics, control, precision engineering, information technology, and systems thinking in the design of products and manufacturing processes. The key spirit of this term is the "synergistic combination," which refers to the system integration approach. The mechatronic product should include features such as functional interaction among the contributing components, spatial integration, intelligence, and reconfigurability/ flexibility. Some typical mechatronic products include the 3C (Computer, Communications, Consumer-Electronics) productions, automobile, household appliances, railways and vehicles, the antilock breaking system (ABS) break, the autonomous mobile robot, etc. The relative literatures about integration aspects can be found as follows: Burmester et al. (2005) presented the visual integration of object-oriented modeling techniques. Pi1 et al. (1996), described a recursive experimental design method for simultaneously optimizing both mechanical structure and control. Kamal et al. (1996), proposed the necessary steps in Mechatronics. Lin et al. (1996) presented the integration of a compact mechanism design for an NTU five fingered dexterous robot hand. The paper, Dario and Coodall (2007), describes the architecture of a multiprocessor system on a chip which is being developed for adaptive, high-performance, embedded real-time control applications.

3. The development of mechatronics components

3.1. Advanced intelligent controller

Usually in motion control, the velocity is estimated from the encoder position, which is the most typical sensory method based on the difference of successive encoder counts. The velocity may also be estimated based on the model-based state estimation theory (Kim and Sul, 1996; Song and Sul, 1998; Kwon et al., 2003). Recent kinematic Kalman filter (KKF) (Jeon and Tomizuka, 2007), an accelerometer-assisted velocity estimation method, was investigated and confirm the superiority in reliability and cost-effectiveness. Lau et al. (2007) proposed a new approach to vibration damping and control. Liu et al. (2006), presented an automated on-board modeling of cartridge valve flow mapping based on a localized estimation method. Fite et al. (2006) presented detailed actuator design with a pair of proportional injector valves, and a force controller. Munir and Book (2002) proposed a stable bilateral teleoperation, which employs a wave-based predictor using a Kalman filter and an energy regulator to cope with unexpected time delays. Panzieri et al. (2002) presented an outdoor navigation system using Kalman filter as the localization algorithm. A sensor fusion problem is discussed by Baeten et al. (2002), and they demonstrated how a vision system can effectively complement a force control to detect corners along the contour. The modeling of chemical kinetics is crucial for the modeling of the three-way catalytic converters (TWC), but it is very difficult. Glielmo et al. (2000) discussed the derivation of a dynamic model for a three-way catalytic converter, which is an interesting yet wide area of automotive mechatronics. They proposed a machine learning algorithm that the reaction kinetics of the system is modeled by a neural network, the parameters of which are tuned via a genetic algorithm.

3.2. Smart sensor and actuator

The five senses, vision, touch, hearing, smell, and taste, provide real-time information of perceiving the external environment for humans. Through the vision organs, we can quickly recognize how an object looks and what it is. Touch sensing, includes the capability to sense the degree of slip, surface compliance, and temperature, supplies important sensory information and helps us manipulate and recognize objects. Sense of hearing is also indispensable for maintaining our daily lives. In addition to these external five sensors, the muscle spindle is well known for detecting the length of muscle, and otolith organs perceive the direction in which acceleration is imparted.

The past 20 years, sensor devices have become highly advanced, especially in the MEMS-related fields, and include optical sensors, piezo-based force or acceleration sensors, chemical sensors, and so on. An intelligent mechatronic system is supported by various sensing components. Vision sensor provides mechatronic system with the most important source of information about surroundings. However, the state-of-the-art artificial vision is still far behind human recognition capability. In recent advancements, the artificial tactile sensors cannot detect the tangential force component result in the performance is not satisfactory. Various internal sensors, e.g., potentiometers, encoders, tachometers, acceleration sensors, and gyrosensors, have been utilized in mechatronic systems such as robots, manufacturing systems, automotive vehicle, and so on.

Yan et al. (2006) presented new mechatronic devices, a multi-degree-of-freedom electrical actuator, for advanced control applications. Odhner and Asada (2006) presented a method for using thermoelectric devices (TEDs) together with a low-order estimator to achieve feedback control of a SMA actuator array. In the paper by Paynter and Juarez (2000), a novel type of pneumatic actuator has been designed to be used as a spherical drive in various jointed-arm or jointed-leg robots. The electrohydraulic actuator proposed in the paper by Habibi and Goldenberg (2000), high torque/mass ratio and modularity are desirable features of the new design. The paper by Maas et al. (2000) presents a model-based control for ultrasonic motors. The paper contributed by Hu and Su (2007) proposes a novel procedure for detecting environmental changes by using a pan-tilt-zoom (PTZ) camera.

Formerly the unobtainable force output of the IPMC (Ionic Polymer Metal Composites) actuator resulted in limited practical applications. Richardson et al. (2003) investigated the control of IPMCs and has been demonstrated that force and position controllers can be effectively implemented on the polymer actuator. Goldfarb et al. (2006) proposed a power supply and actuation system appropriate for a position or force controlled human-scale robot, and described the design and control of a liquid monopropellant actuation system. This paper, Stein et al. (2003), presents mathematical models of spherical encoders, which encode spherical motion in the feedback control of spherical motor systems, based on a finite number of binary sensors and a two-color painting of a ball rotating within a housing. In the paper by Aghili et al. (2007), the design and control of a high-performance direct-drive system with an integrated motor were presented.

3.3. Data fusion

In recent years, multisensor fusion methods play gradually an important role in intelligent applications such as mobile robot navigation, multiple target tracking, and aircraft navigation. In order to use multiple sensors effectively and intelligently, specially designed methods are required for integrating and fusing the data acquired by these sensors of the systems. Some general multisensor fusion methods include weighted average, Kalman filter, Bayesian estimate, and fuzzy logic (Luo et al., 1989). The diagram shown in Fig. 5 represents integrated framework as being a composite of these basic functions for multisensor data fusion. A group sensor provides the input information, which must first be effectively modeled to be used for integration. A common assumption is that the uncertainty in the sensory data can be adequately modeled as a Gaussian distribution. The modeled data from each sensor can be integrated into the operation of the system in accord with three different types of sensory processing: fusion, separate operation, and guiding or cueing. The results of the sensory processing function serve as inputs to the world model. A world model is used to store information concerning any possible state of the environment the system is expected to be operating in.

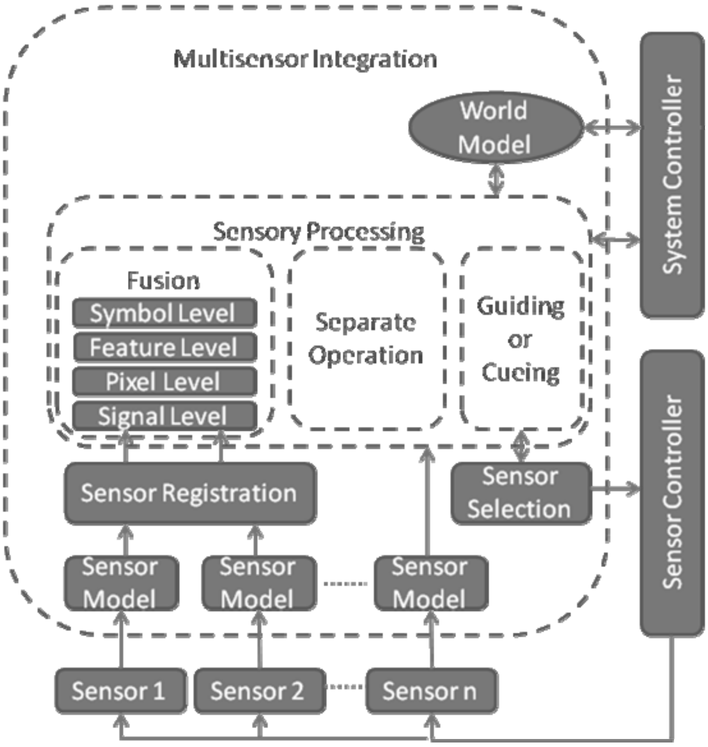


Fig. 5. Functional diagram of multisensor integration and fusion in the operation of a system (Luo et al., 1989).

4. A brief survey of current mechatronic systems:

4.1. Advanced robotic systems

Along with technical progress, there were some breakthroughs, such as the development of the theory of intelligent and robust control, the rapid progress of the system-on-a-chip digital processor, the advancement of CAE/CAD/CAM for mechanical construction implementation, and so on. In the mechatronics field, motion control was the key technology to achieving the solutions required for a wide variety of problems, such as improvement of productivity, reliability, quality in industry faced.

A control method to estimate the unknown friction in a dynamical situation was proposed by Iwasaki et al. (1999) and Sakai et al. (1999), to control the position of the mechanical object with the existence of the friction. Berns et al. (1999) presented an innovative design of a four-legged walking machine, which is able to simulate both mammal and reptile walking modes. A different type of motion technology in the field of walking machines is provided by Müller et al. (2000). They proposed a comprehensive report on nonlinear dynamic models for describing the overall behavior of the large scale walking machine ALDURO, a hydraulically driven anthropomorphically legged and wheeled robot. Natale et al. (2000) addressed a systematic procedure of designing the structure and tune the parameters of a force controller for robots endowed a positional interface. Inoue et al. (2001) described a novel stable motion control strategy for a mobile manipulator with the consideration of external force from the environment. An acceleration controller is used to recover from perturbations due to the external force. Soft computing is a popular research topic among mechatronics engineers in recent years. In the papers, Ito et al. (2001) presented an evolutionary algorithm for the robust motion controller design in mechatronic systems using a genetic algorithm (GA). The proposed design algorithm requires no complicated procedure unlike the conventional design schemes, thus allowing the compensator parameters tuning to be autonomous. Beck and Turschner (2001) proposed the automated startup procedure of a PI state-controlled rolling-mill motor by using evolutionary algorithms as an auto-tuning tool to optimize the motion controller and to make the motion controller autonomous. Godler et al. (2001) presented a method to compensate periodic sensing error of a Harmonic Drive built-in torque sensor and evaluated its performance under load torque and rotational speeds, and addressed a practical sensor integration problem in motion control, i.e., torque sensing using strain gages cemented directly on the reduction gear. Carrozza et al. (2002) proposed a novel biomechatronic design and fabrication of prosthetic hands, which consists of integrating multiple DOFs finger mechanisms, multisensing capabilities and distributed control in order to obtain humanlike appearance, simple and direct controllability and low mass.

A direct-drive robotic manipulator used in semiconductor manufacturing was proposed and demonstrated experimentally by Hosek (2003). Kovecses (2003) made use of differential variational principles of constrained dynamic systems to research the dynamics of parallel robots and mechanisms. A dynamics and control model for heavy-duty electrohydraulic harvester manipulator was presented by Papadopoulos et al. (2003), and the parameters are experimentally identified and validated, leading to a good tracking behavior. The paper by Caccavale et al. (2003) focuses on the dynamic model and control of the Tricept hybrid industrial robot. The macro/micro control problem in the presence of macro flexibilities was studied in the paper by George and Book, 2003. Lee et al. (2003) studied the manipulator interactions with a stiff environment, a nonlinear bang-bang impact controller that independent of the mode of operation is proposed. Nho et al. (2003) presented a control methods, which using the theories of neural network, fuzzy logic and proportional-derivative, to solve the problem of providing accurate parameter estimates for computed-torque control. Doulgeri et al. (2003) presented a feedback grasp controller and stable grasping in rolling manipulations with soft deformable fingertips under two soft-contact motion models. Wang and Xu (2003) described the analysis of the stable full-state tracking and internal dynamics problems of nonholonomic wheeled mobile robots under output-tracking control laws, and presented formulation offers new insight to the zero dynamics of the mobile robot. Sujan and Dubowsky (2003) presented an algorithm based on a mutual information theoretic metric for the excitation of vehicle dynamics, to efficiently estimate the dynamic parameters of mobile robots. The mutual-information-based metric measures the uncertainty of each parameter's estimate, and is used to optimally select the external excitation required to excite the dynamic system effectively. Ji et al. (2003) developed a bond-graph model to model the system dynamics and perform online tracking, fault detection, fault isolation, and fault identification. They also proposed a hierarchical fault accommodation framework that allows the continued operation of the mobile robot with some performance guarantees in the presence of actuator faults.

In most mobile robot localization schemes, the neglect factors of slip, sinkage, and other wheel-terrain dynamic interactions cause the principal cause of tractive problem and odometric accuracy loss. Reina et al. (2006) implemented a multimodal sensor-fusion approach and innovated vision-based algorithm for wheel sinkage estimation to provide deterministic detection of slip and sinkage especially on unpaved rough terrains. The paper by Dean-L´eon et al. (2006) presents the theoretic contribution and experimental validation in the problem of constrained force control with uncalibrated camera/robot and unknown contact friction. The paper by Matsuno et al. (2006) shows an excellent solution to problem—robotic manipulation of deformable objects (such as a rope). Furthermore, they confirmed the effectiveness of their method experimentally in solving a difficult robotic problem commonly encountered in daily life. Huang et al. (2006) considered the automated deployment and maneuver of safety cones used in highway maintenance work zones, and proposed a special centralized localization method for such a group of extremely sensor-limited follower robots. A statistical simulation of the localization method was investigated, which analyzes the choice of appropriate distance between two tracked positions and for the minimum allowable radius of curvature for follower motion. Tang et al. (2006) made use of screw-theoretic analysis tools to provide a systematic framework for formulation and evaluation of system-level performance, and examine cooperative payload transport by robot collectives in an "Army of Ants" approach. Luo and Su (2007) proposed an intelligent security robot provided with fire detecting system, which using adaptive fusion algorithm to fusing the information acquired from smoke sensor, flame sensor, and a temperature sensor. Hwang and Chang (2007) developed a mixed H_2 and H_∞ decentralized control for a car-like mobile robot (CLMR) in an intelligent space to obtain a piecewise line trajectory tracking and obstacle avoidance. Many of the problems, e.g., localization, information about the environment, high computational power, different software, and sensor-based control for each mobile robot, are solved.

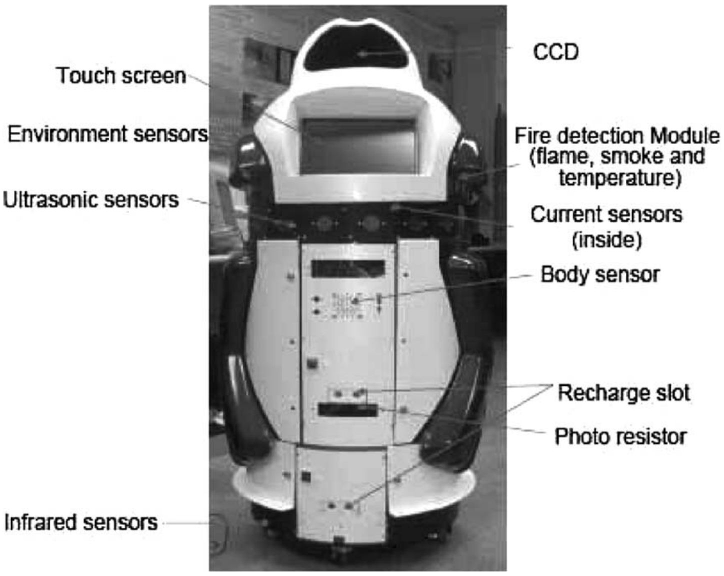


Fig. 6. Overview of intelligent security robot (Luo and Su, 2007).

Murphy and Sitti (2007) designed and implemented the agile small-scale wall-climbing robot utilizing dry elastomer adhesives. The quasi-static model, determining the forces acting on the robot, and the adhesive performance model for a climbing robot was developed, which demonstrates the margin of safety and steady-state operating points. Dollar and Howe (2006) described the realization of novel single-piece compliant robotic graspers that mimic the integrated structural, sensing, and actuation functionality of the human hand. They presented a gripper fabricated using a simple prototyping technique that minimizes construction complexity and increases robustness, while preserving the advantages of passive joint compliance. Agrawal and Fattah (2006) described the unique approach of designing of a planar biped for which the model is nearly linear by judicious placement of counterweights within the system. Dynamic equations of motion for the swing phase and the impact of the biped with the ground were considered as nearly linear with nonlinear perturbations, which tremendously simplifies the development of nonlinear feedback-linearized controllers. Zoss et al. (2006) proposed the first-of-a-kind untethered energy-autonomous exoskeleton prototype, Berkeley's Lower Extremity EXoskeleton (BLEEX)—a powered leg exoskeleton that shadows the operator's movement to enhance the overall load-carrying capabilities in rough, unstructured, and uncertain terrains. McIntosh et al. (2006), and Banala and Agrawal (2005) discussed development and experimental validation of a novel mechanism for biaxial rotation, using a single actuator, of an ornithopter wing, which a compact light-weight mechanism to achieve such coordinated wing motions.

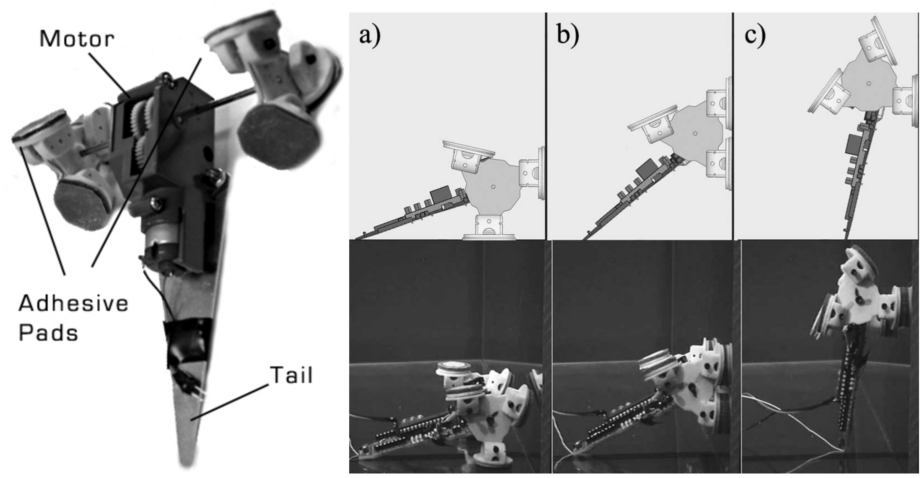


Fig. 7. Waalbot and Schematic side view showing the steps in a 90◦ plane transition (top) and still-photograph frames of the Waalbot prototype erforming the transition (bottom) (Murphy and Sitti, 2007).

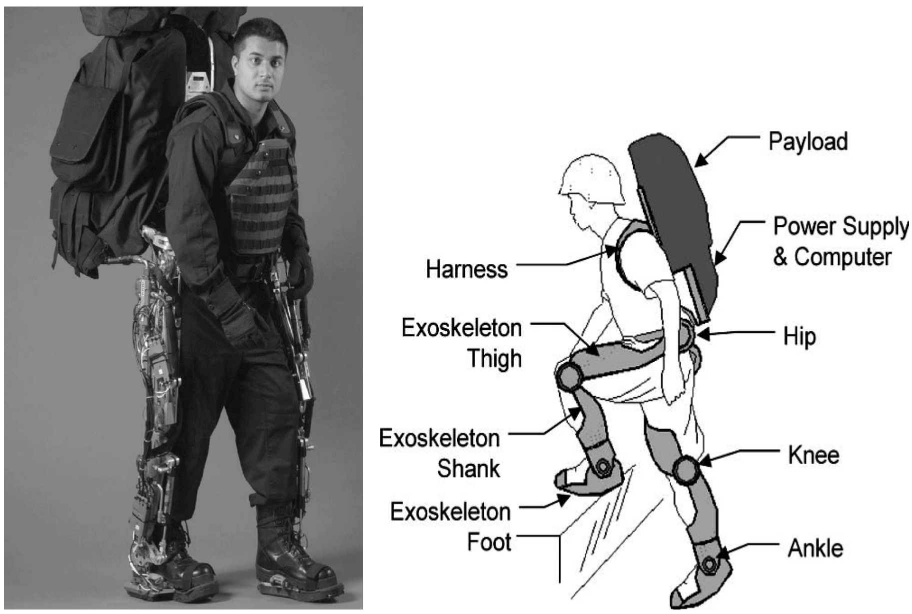


Fig. 8. Final BLEEX design. and Conceptual sketch of a lower extremity exoskeleton. Proper actuation of the robotic legs removes the payload weight from the wearer, while allowing the wearer to effortlessly control and balance the machine (Zoss et al., 2006).

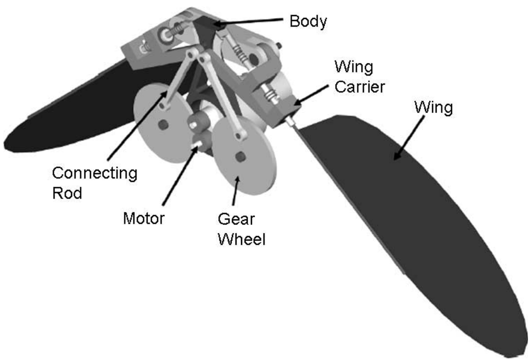


Fig. 9. Labeled three quarters view of the vehicle. The wings are rotated down and the follower rotated upward just above the guide (McIntosh et al., 2006).

Climbing robots can perform many tasks inaccessible to traditional vehicles or humans such as inspection, repair, cleaning, surveillance, and exploration. These papers, Yano et al. (1997); Shen et al. (2005) and Balaguer et al. (2006), present and discuss the design, fabrication, and evaluation of several novel bio-inspired climbing robots. Menon et al. (2004); Santos et al. (2007); Jia et al. (2006); Unvri et al. (2006), and Menon et al. (2005), investigated a gecko inspired climbing robot. Several biological inspired quadruped robots were proposed by Makita et al. (1999); Zhang et al. (2005); Son et al. (2006); Lei et al. (2007), and Duy et al. (2007). Linnemann et al. (1999); Izu et al. (2002); Brown et al. (2007); Yang et al. (2007), and Brunete et al. (2007) investigated snakelike robot. Dog inspired quadruped pet robots were showed by Luo et al. (2005); Luo et al. (2001); Suzuki et al. (2007), and Seiji et al. (2004). Some interesting swarms inspired robots were developed by Gao et al. (2007); Choiet al. (2005); Kingsley et al. (2006), and Arena et al. (2007). The paper, Rifai et al. (2007), introduces flapping wings, flapping micro Unmanned Air Vehicles (UAVs), and a bounded state feedback control torque, based on the theory of cascade, was applied to deal with the attitude stabilization.

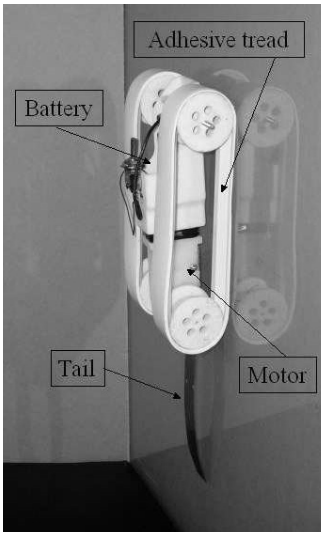


Fig. 10. The tread-based locomotion mechanism (Menon et al., 2004).

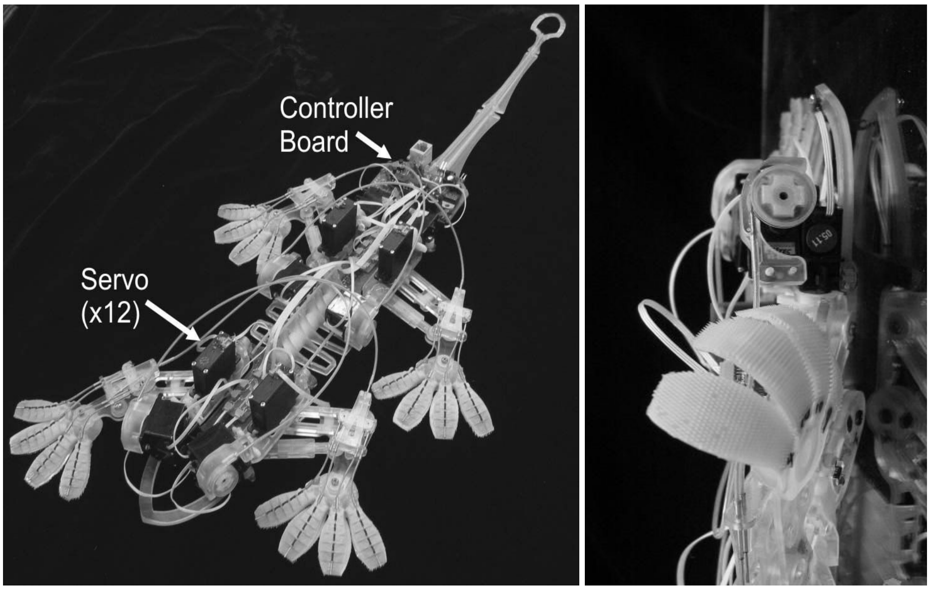


Fig. 11. Stickybot experimental climbing robot for testing directional adhesives. Each limb has two trajectory degrees of reedom (fore-aft and in-out of the wall) and one toe-peeling degree of freedom. The entire robot weighs 370 grams (Santos et al., 2007).

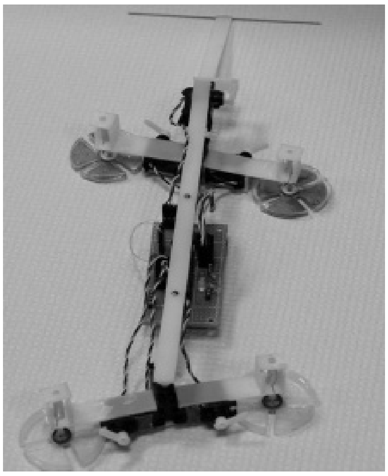


Fig. 12. Geckobot robot (Unvri et al., 2006).

Fig. 13. Prototype of proposed dynamic-walking quadruped robot (Son et al., 2006).

Fig. 14. Robot TIM-1 (Lei et al., 2007).

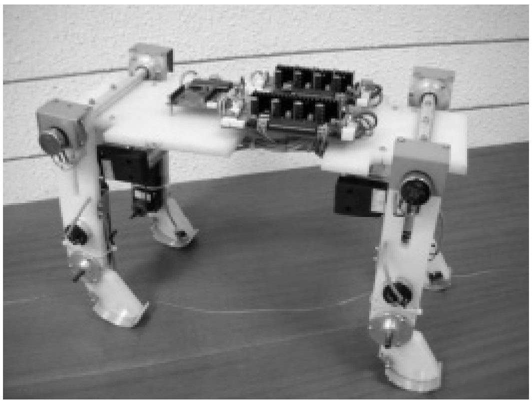
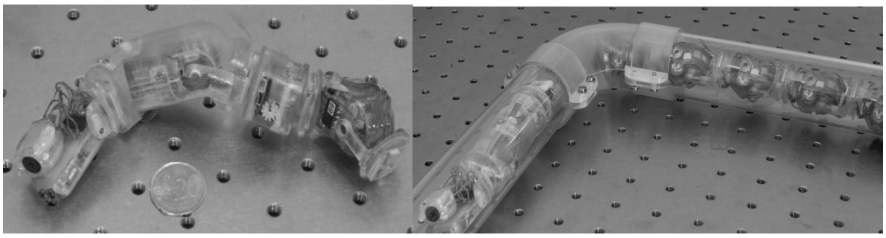


Fig. 15. The prototype of quadruped robot (Duy et al., 2007).

(a) (b) (c)

Fig. 16. (a) The hyper-redundant robot mounted on a mobile base. (b)Integrated joint module with onboard electronics. (c) Gear-cross couples two actuator units and provides joint torque (Brown et al., 2007).



(a) (b)

Fig. 17. (a) Camera, rotation II, support and rotation I modules. (b) The robot inside a pipe (Brunete et al., 2007).

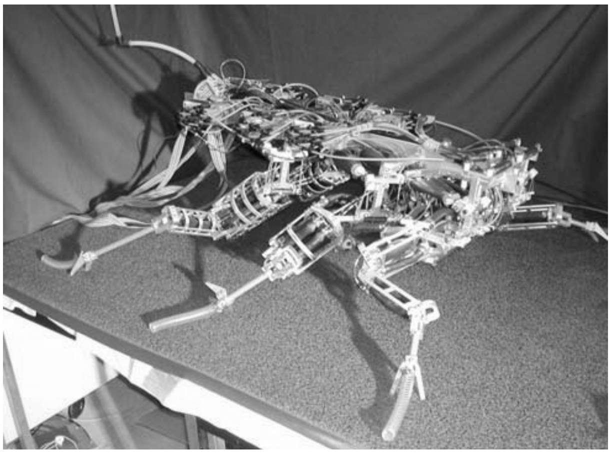
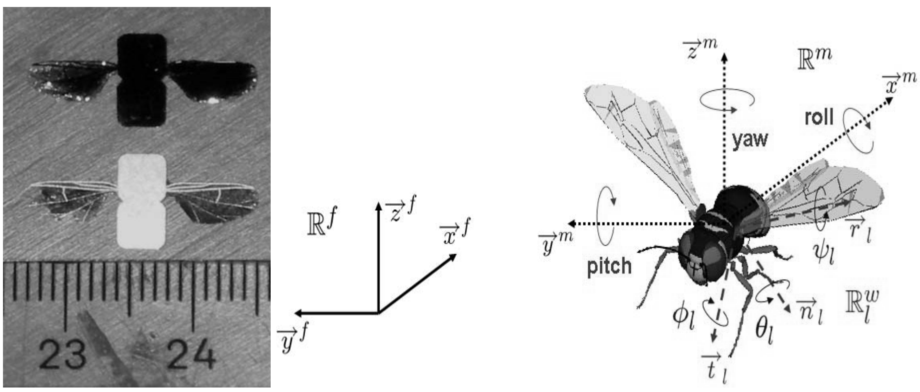


Fig. 18. Robot V can stand and walk with no feedback control (Choiet al., 2005).



(a) (b)

Fig. 19. (a) Centimetric scale prototype of the "OVMI" project. (b) Frames and wings angles (Rifai et al., 2007).

4.2. Micro/nanomechatronics

The micromechatronic system, which encompasses the same concepts as mechatronics in the "macro" world, is the synergetic integration of mechanical, electrical, information, communication and nano/micro level technologies in the design, manufacture and operation of industrial products and processes. Micromechatronic system emphasizes the key factors in integration, intelligence, communication functions which includes actuators/sensors, control of mechatronic systems, nano/microelectromechanical systems (NEMS/MEMS), micromechatronic devices, human-machine interface/haptics, embedded computing and software engineering, networked and embedded micromechatronics and design/integration methodologies for micromechatronic systems etc. Micromechatronics on specific engineering systems to which micromechatronics play key roles, such as: automotive systems, mobile robots, precision motion control systems, consumer electronics, elecommunications, space, medical devices, bio-mechatronics, nano/micro manipulation and nano robotics. In this section, we will briefly discuss the state-of-the-art of intelligent micromechatronics in the macro and nano world and to present recent advances made research results.

Ferreira et al. (2003) presented a new generation of compliant multi degree-of-freedom microconveyors that use direct drive standing wave ultrasonic actuators which were inspired from high-force actuator concepts, and proposed a dynamic model consisting of the piezoelectric arrayed resonator dynamics and the frictional force model. The paper by Shen et al. (2006), considers the use of a closed-loop optimally controlled piezoelectric microforce sensor for micromanipulation and microassembly applications. The developed micro-sensor is based on a cantilevered composite beam structure with embedded piezoelectric polyvinylidene fluoride (PVDF) actuating and sensing layers. When an external load causes a deformation in the sensing layer and immediately, a signal is sent via the optimal controller to the actuating layer which generates a force to counteract the external load, and then remains in the equilibrium position. This sensing determines the applied force device through measurement of the balance force, and shows enhanced stiffness and dynamic range with good sensitivity and high manipulability. Helin et al. (1998) presented the theory, simulation, and experimental results of a critical component of micromechatronic systems that is, ultrasonic micromotors using Lamb and Rayleigh waves. They proposed a model with a quantitative description of motion in friction conditions for calculating key parameters to improve the design of ultrasonic micromotors. Dario et al. (1998) addressed a microrobot with a new type of electromagnetic micromotor, and described in detail the principle, design, fabrication, and performance of the wobble-type micromotor. The microrobot with a volume of 4mm is applied in new instruments for minimally invasive therapy. Arai et al. (1998) illustrated a micromechatronic approach to the design of an important subsystem (the microgripper) of a more complex system for micromanipulation. They proposed a method to deal with this problem of adhesive forces in micromanipulation. Reynaerts et al. (1998) described the implementation of a concurrent-engineering view on microsystem design, and pointed out that this MEMS technology facilitates the way for concurrent engineering of real 3D micromechanical systems integrating sensors, actuators, and processing electronics. Tendick et al. (1998) presented micromechatronic design methods and applications of a micromechatronic millirobotic system for minimally invasive surgery (MIS) developed. Itoh (2000) investigated the biomechatronics problem regarding the possibility of treating protozoa as living micromanipulators. The rapid turning controller and the experimental results were presented. Arai et al. (2003) reported a pinpoint injection method of microtools (MTs) at the desired location of a microchamber, and made use of enhanced laser micromanipulation technology effective in discovery of target microbe without damage it. Sitti (2003) proposed a new principle of piezoelectrically actuated mechanism motion amplification for micro mechanical flying insects. A four-bar mechanism with two flexible links is applied in a micromechanical flying insect thorax design for stroke amplification. El Rifai et al. (2007) proposed a robust adaptive controller applied in an atomic force microscope, that is capable of auto-tuning gains for different cantilever-sample combinations, and compensating for the uncertainties resulting from choice of scan parameters. Fatikow et al. (2007) contributed the development of an automated nanohandling station in a scanning electron microscope (SEM). This station enables handling tasks in the micrometers and submicrometers range, like the handling of TEM-lamella. Hung et al. (2007) constructed a modulation/demodulation scheme to design a novel dual-stage piezoelectric nano-positioner, that successfully extends the measurement range beyond the limit of the wavelength of optical fiber Fabry–Perot interferometer. The paper by Yuan and Yang (2007) presents a novel approach of automated planning for multirobot-based nanoassembly that provides an improved self-organizing map to fit all the nanoassembly tasks into a seamless process, and makes it possible for handling of environmental uncertainty and generating optimized motion paths at run time with a modified shunting neural network.

4.3. Biomechatronics and healthcare

An emergent variant of mechatronics is biomechatronics that integrates the fields of biological science and mechatronic technology. The paper by Mori et al. (2006) presents a "real-life" exoskeleton for healthcare. They described a standing style transfer system for the disabled person, simulated and overcame serious instability problems of conventional powered exoskeleton systems. On the same line, the paper by Kong and Jeon (2006) proposes the tendon-driven exoskeletal assistive device, EXPOS, which consists of a wearable exoskeleton and caster walker to overcome the drawbacks of the exoskeleton for the elderly and the patients to motion, walk, sit down, and stand up fairly well. Menciassi et al. (2003) proposed an innovative prototype miniature robotic instrument consisting of a microfabricated microgripper, instrumented with semiconductor strain-gauges as force sensors, and capable of characterizing the mechanical properties of tiny biological tissues effective in medical diagnosis. Liu et al. (2007) proposed a neurosurgical robot system that they have developed for clinical trials, and discussed how to improve the calibration positioning accuracy by using a revised Denavit–Hartenberg kinematic model and compensation for joint transmission errors using a BP neural network. Rehabilitation medicine is also the main application in biomechatronics field. Masia et al. (2007) investigated a mechatronic device, a single-DOF mechanism with a novel statorless configuration, for rehabilitation of grasping functions. Perry et al. (2007), proposed a 7-DOF anthropomorphic powered-exoskeleton for the upper limb. The cable-actuated dexterous exoskeleton offers remarkable opportunities as a versatile human–machine interface and as a new generation of instrumentation for assistive technology. Zollo et al. (2007) proposed a biomechatronic approach to the design of an anthropomorphic artificial hand with self-adaptive grasp that mimics the natural motion of the human fingers. Tanaka et al. (2007) investigated a compact tactile sensor system based on polyvinylidene fluoride (PVDF) film, and intended to enhance tactile capabilities of artificial hands for Braille automatic reading. Tung et al. (2007) presented a mechatronic device for minimally invasive and teleoperated surgery. The proposed actuator made from laser-machined shape memory alloy (SMA) tubes, and provides actuation locally to the desired point of manipulation, thus, greatly improving the physician's ability to intervene in diseases. Mitsuishi et al. (2007) proposed a remote operating system for laparoscopic minimally invasive teleoperated surgery that is providing force feedback to the operator.

4.4. Automotive mechatronics

The burgeoning automotive industry impacts the social, environmental, economic, and technological aspects of our daily life. More and more mechatronic systems were investigated in automotive application, including antilock braking systems, supplemental restraint systems (air bags), cruise control, and traction control. Mechatronic systems play a more important role for improving automotive functionality, safety, economy and comfort, and the designed functions assist the driver to prevent unstable or unpredictable behavior and to stabilize the motion of the automobile. The complex capabilities of fault detection and diagnosis are achieved by the integration of several burgeoning technologies in the field of actuators, sensors, data processing, and so on.

In the traditional valve-controlled hydraulic elevator, when the vehicle moves downwards, the entire potential energy of the vehicle is wasted and converted into fluid heat by throttling. To reduce the energy consumption and power installation requirements, Yang et al. (2007) designed a novel micro-controller-based energy-regenerating hydraulic elevator using an accumulator as the energy restoring component, which would be reduced to a level at par with that of an electrical elevator. Fischer et al. (2007) proposed the concepts of model-based fault detection and diagnosis along with sensor fault tolerance for automotive system, and realized a vehicle lateral dynamics system and an active suspension system. Arimitsu et al. (2007) developed a new safety driving system that employs seat-belt vibration to stimulate and awake drivers. In the field of combustion engine control, the application of hybrid modeling and receding horizon optimal control techniques were proposed by Giorgetti et al. (2006). Hattori et al. (2006) overcame the problem of obstacle avoidance in automotive motion. They propose an optimum trajectory based on the framework of the so-called H-VDIM algorithm for vehicle dynamics control. Deur et al. (2006) presented a survey paper of the authors' work in the field of modeling, analysis, and validation results of automotive power train systems and their components. They showed a functional description of an automotive power train system, followed by the modeling of electronic throttle mechanism, manifold air temperature and pressure measurement in engine, torque converter fluid dynamics modeling, wet clutch fluid dynamics, automatic transmission, and tires. Isermann (2008) contributed a review paper describing the increasing mechatronic design, systematic development chains, from modeling and design to implementation and testing in automotive industry.

4.5. Haptic devices and applications

The word "Haptic" was derived from the Greek "haptikos" meaning "to touch," also may be defined as proceeding from the sense of touch. The sensory information of haptic is divided into tactile and kinesthetic. Tactile sensing gives a perception of surface textures and geometry such as temperature, skin curvature and stretch, vibration, slip, pressure, and contact force. Kinesthetic information caused by physical forces applied to the body is sensing and awareness of body position and orientation, so-called proprioception.

Haptic interface is a device with the ability that transforms that sensory information in their original form to the operator. For example, surgical simulation where students can practice surgical procedures on virtual models, and human–machine interfacing where operators can feel the graphical user interface. Dreaming the situation, supplier provides a haptic interface for customers to feel and touch a product in a remote location before making a purchase. On the other hand, the applications of that allows for the remote control of robots, so-called telerobotics, are those based on real haptics that is sensed and then regenerated by the haptic devices. It enables the possibility to manipulate and feel objects remotely.

In the past decade, the explosive advances in information science, NEMS/MEMS, networking technology and semiconductor industry have had effects on the field of haptics. Not only are such components now reachable, but the commercial products are only limited by the imagination.

A novel haptic mouse was developed by Kyung et al. (2007), and offered the ability of displaying properties such as patterns, gratings, and roughness. Gao and Book (2006) examined the use of passive electromagnetic brakes and presented a novel multimodal haptic user interfaces with enhanced motion redirection and force control. Humans hand exhibits highly asymmetric input–output bandwidths and sensing sensitively to the high frequency accelerations. The capability of discerning material properties, such as hardness and texture, depends on high-frequency feedback. Yet in order to keep system stability, the high frequency information in feedback band is always neglected entirely during teleoperating remote robot. Tanner and Niemayer (2006) presented the control architecture that both incorporate this important information and provide the natural ability to scale and shape the high-frequency content independently of the low-frequency force feedback.

Fig. 20. Prototype of the texture display mouse (Kyung et al., 2007).

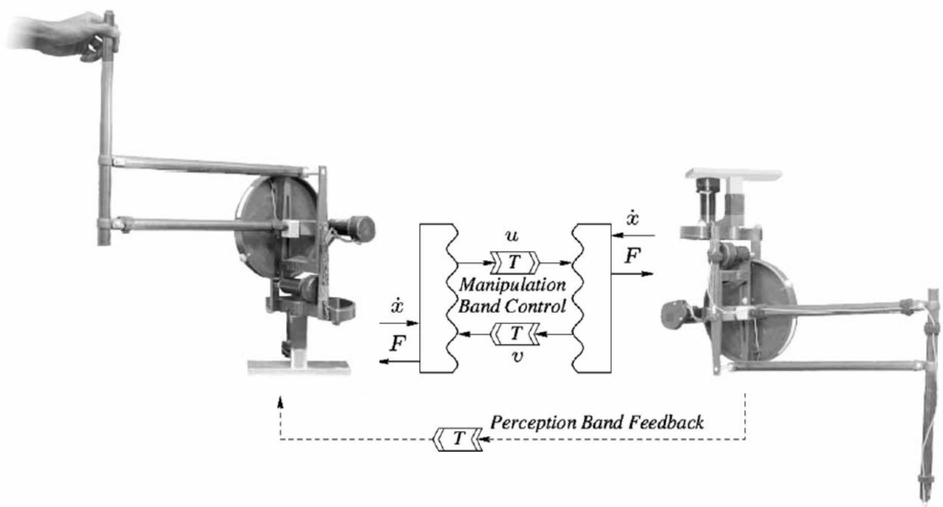


Fig. 21. The telerobotic system consisting of two toolhandles (Tanner and Niemayer, 2006).

4.6. Consumer-electronics productions

Janschek et al. (2007) studied the performance of a camera stabilization consisting of a real-time camera vibration detector and a piezoelectric actuators as high precision focal plane adjuster. They said that the visual servo was used to minimize the size of the optical device and to improve the sensitivity to attitude disturbances.

Stefanopoulou and Suh (2007) described a comprehensive overview of fuel cell technology, and proposed the technical integration in the mechatronics field, including chemical, fluid, mechanical, thermal, electrical, and electronic subsystems. The paper by Horowitz et al. (2007) discusses the most important advancements in recent years in magnetic hard disk drive servo systems, which may have to be deployed in the near future to sustain the continuing 60% annual increase in storage density of these devices. They proposed two mechatronic innovations: First, in order to improve the precision and track-following capability of the read/write head positioning control system, the use of high bandwidth dual-stage actuator servo systems was innovated. Secondly, the instrumentation of disk drive suspensions with vibration sensing strain gages was employed to enhance airflow-induced suspension vibration suppression in hard disk drives.

5. The future of automatic systems:

5.1. Current trends in mechatronic systems

Based on current trends, this paper offers some projections to the future, including various mechatronic applications as well as developments in group machines interaction, human-machine communication and cooperation, machine autonomous and intelligent, such as learning, planning, communicating, and sociable. The development of mechatronic products for many fields (such as entertainment, military applications, aerospace industry, industrial manufacture, household services, care of elderly and people with disabilities, and so on.) has become the primary factor for maintaining high living standards for all industrialized nations in today's world. For example, the case study of household services presents an intelligent security robot system, NCCU Security Warrior, capable of fire alarm and intruder detection (Luo et al., 2007). When the Security Warrior detects a fire alarm, it immediately rushes to fire field and tries to extinguish the fire. At the same time, Security Warrior sounds alert, flashes the light and sends warning message by GSM device to the cell phone of house owner. In another scenario, Security Warrior detects an intruder, and immediately triggers alarm, sends GSM message to security department, chases the intruder, tracking his face via CCD camera in robot, and then sends the image to security personnel.

In fact, Security Warrior is a multifunction service robot which can achieve more complex task than foregoing functions, such as care of elderly and people with disabilities, home cleaning, etc. In order to autonomic accomplish the complex task, the developed service robot must be capable of the fundamental capabilities including object following and tracking, obstacle detection and avoidance, autonomous navigation, supervises via electro-network, a remote manipulated vision system, human-robot interaction (HRI), multisensor data fusion and so on. Many various multifunction robots, similar to Security Warrior, have been developed. The famous R&D groups MIT, IROBOT in America and SONY, HONDA in Japan have invested in advance robotics such as entertainment robots, military robots, service robots, etc. The developments of robotics continually have been published in recently year by more and more research organizations. For example, ASIMO (Sakagami et al., 2002) was made by HONDA and University of Tokyo proposed Human Robot-HRP (Kaneko et al., 2004). In Japan, security robot has become more and more popular by people and companies such as ALOSK, FSR and SECOM.

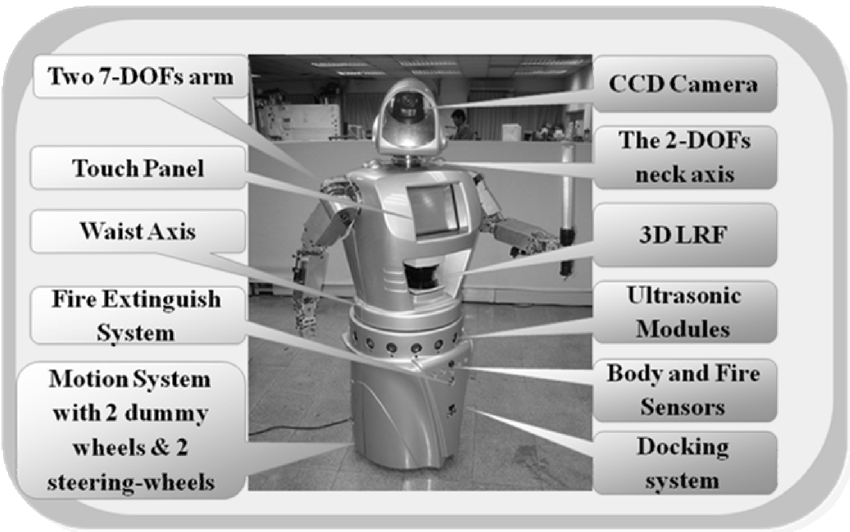


Fig. 22. System architecture of Intelligent Security Robot (Luo et al., 2007).

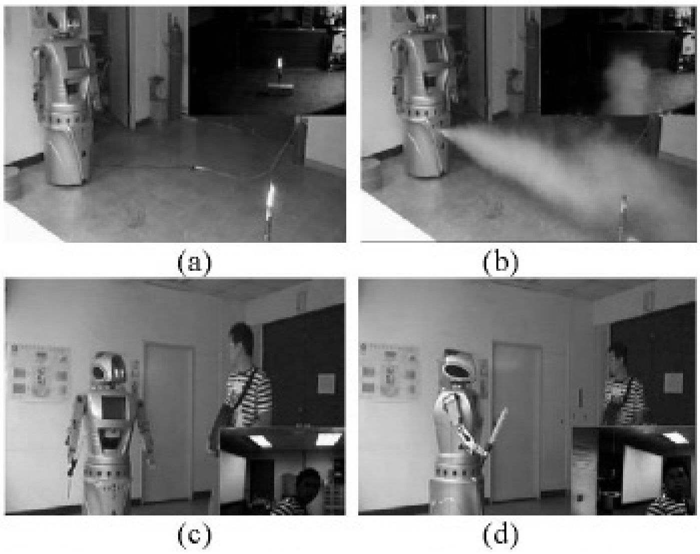


Fig. 23. Fire extinguish system and intruder frightening system.

5.2. Human-machine cooperation and interaction

It is evident from the foregoing description that most of them will base on the capability of human-robot cooperation, to work side by side on common space. This is one of the major trends in the next decade. The next future trend is that humans and machine will be able to intercommunicate through speech using natural language, as well as through gestures and body positions. Robot will be capable of autonomic learning from human via observation and imitation and then transmit the skills they have learned to other robot.

It is interesting thing concerns enabling robots to understand, react to, and display emotions. This implies the ability to sense and understand body language, facial expressions, tone of voice, gestures, and other manifestations of emotional states. Furthermore, the expression and understanding of emotional states are important parts of human-robot communication. Further said, to develop esthetic sense and ethical awareness for robot are not only possible, but likely.

5.3. Micro- and nanorobots

Within the next ten or twenty years, the rapid development in MEMS/NEMS will urge microrobot/nanorobot to be realized and lead to amazing new applications. Even today it is realizable to design a centimeter scale robot, so-called superminirobot, that contains a processor, a camera and one or more other sensors, a motor and controller, a radio, and a battery. We can envision the application that a molecular-sized nanorobots is injected into the bloodstream of a patient. They should be able to locate and destroy tumors, repair aneurisms, and perform a variety of other surgical procedures.

5.4. Reconfigurability

The self-reconfigurable robots are an autonomous mechatronic systems equipped with control unit, sensors, actuators, power supply, networking unit, and most importantly, reconfigurable modules. In order to meet the demands of the environment, the self-reconfigurable robots can autonomously change their physical reconfigurable modules to join with other modules under computer or human command. With the deformable capability, these robots can go beyond the traditional, fixed-shaped robotic systems, and promise versatile capabilities for a wide range of applications, low cost for constructions, and self-repairing for fault tolerance. The potential applications for self-reconfigurable robots are tremendous.

The control issue of a self-reconfigurable robot is a great challenge. In order to execute the desired global action in a given environment, each module, an autonomous and intelligent agent, must cooperate with others.

The self-reconfigurable function can be implemented in several ways, e.g., physical configuration (the structure or shape of the system), connective configuration (a communication network topology), decentralized controllers (concurring and self-coordinating with global and local actions in the current configuration).

Ultimately, the autonomous self-reconfigurable robots must contain excellent characteristic, such as dynamically, to deal with the deformation in constructional topology; asynchronism, to coordinate each agent with individual clocks; adaptability, to maintain growable structures and alterable shape; collaboratively, coordinating all local actions to provide fault diagnosis, damages recovery and fault-tolerance; self-adjustability, to make a estimation of the appropriate configuration which is required to conform the variation of environment (Murata and Kurokawa, 2007).

5.5. Self-organization, self-repair, autonomous evolution, and self-replication

The visualizing scenarios of autonomic machine have been the stuff of many science fiction stories for a long time. The question of machine self-replication is the concern of serious scientists who view self-reproduction as the eventual goal of intelligent machines.

Whether true self-reproducing will realize on the horizon? Perhaps they should never exist. Self-repair is a much less controversial issue and much more feasible. Along with the technologies of fault diagnosis and self-maintenance developed vigorously, machines will be able to repair their own failures within the next ten to twenty years.

To design and implement a sociable machine is the goal that many scientist work diligently allover life. A few key aspects of human social intelligence were characterized to derive a list of core ingredients for sociable machine, such as being there, life-like quality, human aware, being understood, socially situated learning (Cynthia L. Breazeal, 2002). Furthermore, the issue inspired by human societies indicated that very large colonies of robots will require some form of organization. It can be visualized that the development of sociable machine will make it possible for groups of sociable machines to organize themselves into operating units most appropriate to a given task. Finally, several past literatures demonstrate that evolutionary or genetic algorithms are very useful optimization tools that can be used to select appropriate machine parameters to accomplish particular goals.

If the goals of autonomous evolution to be set by the machine themselves, or by humans interested in developing supermachines, the results would be unpredictable.

Conclusion

In this paper, the development of mechatronic engineering in the past and current is described, and the future trend is discussed. A multitude of commercial products were realized by the integrated technologies of mechatronics engineering. From the observation of the progress direction in domain, more and more powerful, intelligent, instamatic (instant plus automatic) functions are required and be realized. The integrated technologies have not been limited in mechanical and electronic area. More scientific disciplines are involved to improve the capability of mechatronic system. In past years, the development tools are more and more consummates, for example, RP/RT/CAE/CAD/CAM for mechanism design, and Integrated Development Environment (IDE) platform for electronic functional design and implementation. The most important improvements are modulized and levelized design concepts, that make the designer escape from a mire of moderating a complicated inter-disciplinary problem, and be absorbed in the development of individual function, especially, in intelligent control, autonomous motion, and so on. This contribution summarizes ongoing developments for mechatronics engineering, reviews of technical literatures and proposes the viewpoints of expectation and perspectives of future development.

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