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'Mechatronics' The Cutting-Edge Technology in Dentistry- A Review

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Abstract

Modern dentistry has seen a dramatic change as a result of the multidisciplinary field of mechatronics, which combines mechanical engineering, electronics, computer science, and control systems. Mechatronic principles have improved dental care's accuracy, efficiency, and personalization by fusing clinical tools with intelligent systems. Dental professionals are already using its applications in a variety of dental specialties procedures. In general, mechatronic systems improve patient experience, lower human error, promote evidence-based decision-making, and increase diagnostic and therapeutic accuracy. Mechatronics' ongoing development holds promise for a new era of patient-centered, intelligent, and minimally invasive dentistry.

Keywords: Mechatronics; Dental Technology; Smart Dental Devices; Sensors in Dentistry; Robotics in Dentistry; Dental Automation

INTRODUCTION

In order to develop and optimize complex systems, goods, or procedures, the multidisciplinary engineering field of mechatronics combines mechanical engineering, electronics, computer science, control systems, and systems design. It makes it easier to create smart devices and intelligent systems with precise control and self-sufficient capabilities. Innovations in automation, robotics, and biomedical devices, including those used in dentistry, are made possible by the collaboration between these fields. [1]

Mechatronic Systems using in Dental Procedures

Modern dentistry has been completely transformed by mechatronic systems, which make dental procedures much more precise, effective, and minimally invasive. An in-depth explanation of how mechatronic concepts relate to different dental procedures is provided below:

The fundamental mechatronic ideas that underpin the construction and operation of contemporary dental technologies. These ideas serve as the foundation for intelligent, responsive, and minimally invasive dental technologies that improve patient comfort, treatment results, and diagnostic precision. [1,2]

Sensors and Transducers

Detect physical changes (pressure, temperature, position, light, force) and convert them into electrical signals.

Example: Pressure sensors in smart toothbrushes or apex locators.

1. **Actuators**

   Devices that convert electrical signals into mechanical motion (e.g., motors, solenoids).

   Example: Electric micromotors in endodontic handpieces.

2. **Microcontrollers and Embedded Systems**

   Small computing units that process inputs from sensors and control actuators.

   Example: Embedded chips in electronic apex locators or digital impression systems.

3. **Feedback and Control Systems**

   Maintain system stability and accuracy by constantly monitoring output and adjusting inputs.

   Example: Torque and speed control in rotary endodontic motors.

4. **Signal Processing**

   Filtering, amplifying, and analyzing signals from sensors to produce reliable outputs.

   Example: Processing bio-signals in pulp vitality testers.

5. **Robotics and Automation**

   Use of programmable machines to perform precise, repetitive, or minimally invasive procedures.

   Example: Robotic arms in CAD/CAM milling or implant surgery.

6. **Artificial Intelligence (AI) and Machine Learning (ML)**

   Systems that learn from data to make predictions or decisions without explicit programming.

   Example: AI-based diagnostic tools for oral pathology.

7. **Computer-Aided Design and Manufacturing (CAD/CAM)**

   Digital design and automated fabrication of dental prostheses.

   Example: Milling crowns and bridges from digital scans.

8. **Human-Machine Interface (HMI)**

   Interaction systems between users and machines (e.g., touchscreens, apps, voice control).

   Example: Smartphone-controlled dental devices.

9. **Wireless Communication and IoT (Internet of Things)**

   Enables data sharing between dental devices, apps, and cloud systems.

   Example: Smart toothbrushes syncing data to mobile health apps.

These ideas serve as the foundation for intelligent, responsive, and minimally invasive dental technologies that improve patient comfort, treatment results, and diagnostic precision.

Role of Mechatronic Principles in Various Dental Speciality Procedures

Modern dentistry has been completely transformed by mechatronic systems, which make dental procedures much more precise, effective, and minimally invasive. In dentistry, the application of mechatronic principles improves patient outcomes, therapeutic precision, and diagnostic accuracy. Mechatronics will become increasingly important as dental technologies advance, allowing for more individualized, digitally driven, and minimally invasive procedures. An in-depth explanation of how mechatronic concepts relate to different dental procedures is provided below:

1.The Role of Mechatronic Principles in the Periodontic Procedures

a) Automated Periodontal Probing Systems

Mechatronic Principle: actuators with force control and feedback systems based on sensors. Automated periodontal probes, like the Florida Probe, record probing depths with digital accuracy and minimize operator variability by using electronic sensors and a standardized probing force (20–25 grams). This reduces tissue damage and improves reproducibility. [1,2]

b) Electronic Plaque Assessment and Biofilm Sensors

Mechatronic Principle: combining microelectromechanical systems (MEMS) with biosensors. Biosensors are used in advanced diagnostic tools to identify particular bacteria or enzymes that are a sign of active periodontal disease. These tools provide sulcus biochemical analysis in real time. In periodontology, mechatronic principles are essential for improving diagnostic precision, lowering human error, and standardizing practices. [3]

2. Mechatronics in Oral Medicine and Radiology

a) Computer-Aided Lesion Detection

Mechatronic Principle: combining AI with real-time feedback systems and image processing. In order to automatically detect carious lesions, mucosal alterations, or early neoplasms, AI-powered systems equipped with mechatronic sensors examine intraoral images or radiographs. These systems aid in the early identification of illnesses that may be cancerous. [4]

b) Intraoral Scanners with Mechatronic Feedback

Mechatronic Principle: data processing, laser scanning, and 3D motion detection. Real-time 3D images of the oral cavity are produced by intraoral scanners (such as iTero and TRIOS), which can help diagnose recession, occlusal wear, and abnormalities in gingival architecture. To avoid imaging errors and optimize scanning trajectories, they make use of embedded sensors. [5]

c) Cone-Beam Computed Tomography (CBCT)

Mechatronic Principle: Revolving arms with precise motion control and feedback systems. High-resolution, three-dimensional scans of maxillofacial structures are captured by CBCT systems using rotating arms powered by stepper motors and feedback controllers. These devices guarantee precise voxel alignment with low radiation levels. [6]

d) Robotic X-ray Positioning Systems

Mechatronic Principle: Real-time motion control and programmable actuators. Robotic arm systems are used in contemporary panoramic and cephalometric X-ray machines to automatically position the imaging head and patient for the best exposure and angle. Mechatronic control lowers operator error and increases reproducibility. [7]

e) AI-Driven Diagnostic Imaging Platforms

Mechatronic Principle: combination of deep learning and machine vision in sensor-embedded systems. These systems, which are frequently cloud-integrated, assess radiographic results for anomalies such as lesions or bone loss. They improve the diagnosis of periodontal and periapical diseases. The future of precision dentistry is being shaped by the convergence of robotics, artificial intelligence, sensor technologies, and control systems, which will lead to more predictable and patient-centered results. [8]

3.Role of Mechatronic Principles in Prosthodontics

Prosthodontics has advanced significantly as a result of mechatronics, an interdisciplinary field that combines robotics, electronics, mechanical systems, and intelligent computer control. In this area, it is essential for increasing accuracy, cutting down on procedure time, and boosting patient-specific results.

a) CAD/CAM in Fixed and Removable Prosthodontics

Mechatronic Principle: Combining computerized control, CNC milling, and 3D scanning. Crowns, bridges, inlays, and dentures are designed and milled using mechatronic subsystems in CAD/CAM systems such as CEREC. This minimizes the need for clinical adjustments by guaranteeing constant accuracy in fit, occlusion,

and margins. [9,10]

b) Digital Impressions and Intraoral Scanners

Mechatronic Principle: mechanical motion tracking and optical sensors. 3D models of dental arches are created by devices such as the TRIOS and iTero scanners, which combine motion-stabilized scanning arms with optical sensors. Better treatment planning and prosthesis fabrication are facilitated by this. [11]

c) Virtual Articulators

Mechatronic Principle: Motion-tracking and simulation technologies. Virtual articulators use mechatronic input from jaw tracking devices to digitally replicate mandibular movements. Dentists can now see occlusal interactions under dynamic conditions thanks to this. [12,13]

d) Mechatronic Denture Fabrication

Mechatronic Principle: additive manufacturing (three-dimensional printing) and robotic milling. The processing of baseplates and tooth arrangement in complete dentures is automated by robotic systems. This results in more accurate function and aesthetics as well as quicker workflows. [14]

e).Oral Implantology

In oral implantology, mechatronic concepts are essential for improving surgical accuracy, lowering risks, and facilitating real-time monitoring and feedback. Implant dentistry is gradually changing toward minimally invasive, patient-specific, and extremely dependable treatment modalities due to the convergence of robotics, digital imaging, sensor technology, and AI-driven control systems.

Advances in mechatronics, which integrate mechanical parts, electronics, control systems, and software to improve implant procedures' accuracy, safety, and predictability, have had a significant positive impact on oral implantology. To enhance patient outcomes, mechatronic principles enable real-time monitoring, robotic-assisted surgery, and digital planning.

1. Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM)

Mechatronic Principle: automated digital process that combines milling machines, design software, and 3D scanning. Accurate implant placement and excellent prosthetic fit are ensured by the precise design and fabrication of surgical guides and implant prostheses made possible by CAD/CAM systems. [5]

2. Robotic and Navigation-Assisted Implant Surgery

Mechatronic Principle: combining feedback control, real-time imaging, sensors, and robotic arms. Robotic systems like Yomi reduce human error during drilling and implant placement by improving surgical accuracy through haptic feedback and robotic guidance. [15]

3. Sensor-Enabled Implant Tools

Mechatronic Principle: Surgical handpieces with integrated force and torque sensors. By preventing

excessive pressure, these sensors lower the risk of implant failure and bone damage in real time. [16]

4. Digital Imaging and 3D Navigation

Mechatronic Principle: coupled with software navigation and cone-beam computed tomography (CBCT). Navigation systems and high-resolution 3D imaging allow for accurate intraoperative guidance and preoperative planning. [17]

5. Robotic-Assisted Implant Placement and Prosthesis Delivery

Mechatronic Principle: robotic systems that are automated and can carry out surgical procedures. Accuracy and repeatability in implant and prosthesis placement are enhanced by robotic devices. [18]

6. Postoperative Monitoring and Smart Implants

Mechatronic Principle: implants have sensors built in to track load and osseointegration. Clinicians can be informed of early indications of implant failure by smart implants' ability to track biological markers and biomechanical stressors. [19]

4.Mechatronics in Oral & Maxillofacial Surgery

a) Robotic-Assisted Implant Surgery

Mechatronic Principle: Robotic drill positioning devices are integrated with pre-operative planning software. Robotic arms are used by systems such as Yomi® to guide osteotomy and implant placement, increasing precision and reducing human error. [20]

b) Surgical Navigation Systems

Mechatronic Principle: Pre-operative planning software is combined with robotic drill placement devices. Systems like Yomi® use robotic arms to guide implant insertion and osteotomy, improving accuracy and decreasing human error. [21]

c) Mechatronics in Distraction Osteogenesis

Mechatronic Principle: Feedback control and microactuators that can be programmed. In mandibular and midfacial reconstructions, motorised distractions provide controlled and progressive bone elongation. These intelligent distractions can be programmed to adjust to each person's unique healing style. [22]

d) 3D Printed Surgical Guides and Plates

Mechatronic Principle: Combining 3D additive manufacturing with CAD/CAM. Mechatronic workflows improve accuracy and cut down on surgery time by producing personalised surgical guides for osteotomies and implant placement. [23]

e) Robotic Jaw Simulation and TMJ Diagnostics

Mechatronic Principle: Joint sensors and electromyography are integrated into motion analysis systems. To

aid in diagnosis and prosthodontic rehabilitation, these devices examine the temporomandibular joint (TMJ) function and jaw kinematics. In oral and maxillofacial surgery, the use of mechatronic concepts promotes increased precision, customisation, and effectiveness. By bridging the gap between clinical expertise and technical accuracy, echatronics improves patient satisfaction and treatment results. [24]

5. Mechatronics in Orthodontics

Numerous dental specialities have advanced thanks in large part to mechatronics, which is the fusion of mechanical engineering, electronics, computer science, and control systems. Personalised therapy, computerised diagnostics, and more precise therapeutic interventions have all been made possible in orthodontics by mechatronic devices.

a) Digital Orthodontic Planning Systems

Mechatronic Principle: Combining robotic wire-bending, software simulation, and 3D imaging. Digital treatment plans are created by systems such as SureSmile and Invisalign using intraoral scanners and cone-beam CT data. Based on these models, robotic arms bend archwires with sub-millimeter accuracy. [25]

b) Smart Brackets and Sensors

Mechatronic Principle: Force sensors, MEMS (Micro-Electro-Mechanical Systems), and wireless data transfer. Real-time monitoring of the force and direction applied to teeth by smart brackets with sensors enables improved force management and shorter treatment times. [26,27]

c) Accelerated Orthodontics Using Mechatronics

Mechatronic Principle: Low-level laser treatment (LLLT) equipment with electronic controls and vibratory stimulation are used. By stimulating bone remodelling mechanically or through photobiomodulation, devices such as AcceleDent and OrthoPulse shorten the length of orthodontic therapy. [28]

6. Mechatronics in Pedodontics

a) Behavior Management Systems

Mechatronic Principle: audiovisual stimulation, robotics, and sensor-based feedback. Children with anxiety are helped by robotic companions such as "Humanoid robots" and audiovisual distraction devices. They cooperate better when they react to word or facial signals. [29]

b) Automated Caries Detection Devices

Mechatronic Principle: robotics, sensor-based feedback, and audiovisual stimulation. Audiovisual distraction gadgets and robotic companions like "Humanoid robots" can aid children who suffer from anxiety. When they respond to facial or verbal cues, they collaborate more effectively. [30]

c) Pediatric Vitality Testing and Smart Pulp Testers

Mechatronic Principle: electromagnetic stimuli that can be programmed and sensors that are micro-

controlled. With more precision and less discomfort, advanced pulp testers evaluate the pulp viability of young permanent teeth using programmable pulse output and feedback mechanisms. Innovative treatment interventions, better patient collaboration, and more precise diagnoses are being made by physicians through the integration of intelligent sensors, robotics, and control systems. [31]

7.Mechatronics in Oral & Maxillofacial Pathology

a) Automated Histopathology and Slide Scanners

Mechatronic Principle: algorithms for image processing, optical sensors, and high-speed motors. High-resolution imaging of tissue samples for AI-assisted pathology and remote diagnostics is made possible by digital pathology scanners. Reproducibility and diagnostic effectiveness are enhanced by these systems. [32]

b) Tissue Engineering and Biofabrication

Mechatronic Principle: combination of robots, 3D bioprinting, and exact microenvironment control. 3D scaffolds for soft tissue or bone regeneration are created by mechatronic bioprinters. Follow-up for tumour excision and reconstruction of maxillofacial defects depend heavily on these systems. [33]

c) AI-Driven Lesion Detection in Oral Pathology

Mechatronic Principle: Digital imagery and diagnostic sensors are combined with machine learning algorithms. Based on trained datasets, AI-powered diagnostic tools distinguish between benign and malignant lesions in the oral cavity using mechatronic sensors and digital image processing. Oral and maxillofacial pathology is changing more and more due to mechatronic concepts. The role of mechatronics in digital, personalised dentistry will only grow as it develops further. [34]

8. Mechatronics in Endodontics

Modern endodontics is revolutionised by mechatronics, a multidisciplinary field that combines robotics, electronics, mechanical engineering, and control systems. In both individual and community-level dental treatment, mechatronic devices enhance clinical precision, decrease human error, and support data-driven decision-making through improved root canal instrumentation and AI-based epidemiology tools.

a) Electronic Apex Locators (EALs)

Mechatronic Principle: circuits that are regulated by feedback and rely on impedance for sensing. By using electric resistance or impedance values to estimate root canal length, EALs increase working length determination accuracy and lessen the need for radiography. [35]

b) Rotary and Reciprocating Endodontic Motors

Mechatronic Principle: electric micromotors, integrated sensors, and torque control systems. With torque and speed regulators, modern rotary endodontic devices (such X-Smart and VDW Gold) allow for safe canal preparation with a lower chance of instrument separation. [36]

c) Endodontic Obturation Devices

Mechatronic Principle: dynamic pressure mechanisms and programmable heat control. In order to improve 3D root canal sealing, devices like as the System B or Elements Obturation Unit use precise heat controls to administer gutta-percha in warm vertical compaction. [37]

d) Microrobotic Endodontic Irrigation Devices

Mechatronic Principle: automatic feedback systems with ultrasonic activation. With the help of integrated sensors, systems like EndoActivator® and GentleWave® use fluid dynamics and acoustic energy to remove biofilm and debris from canal walls. [38]

9. **Mechatronics in Public Health Dentistry**

a) Teledentistry and Remote Diagnostics

Mechatronic Principle: combining AI, mobile cameras, and digital sensors to enable remote communication. Platforms for teledentistry do remote screenings, particularly in underprivileged populations, using intraoral cameras, cloud-based software, and mechatronic accessories.[39]

b) AI-Based Screening and Surveillance Tools

Mechatronic Principle: Mechatronic data platforms with AI capabilities for mapping oral diseases. In order to facilitate evidence-based planning and disease tracking, these systems gather and evaluate data on oral health in the community using wearable technology and smart tablets. [40]

c) Mobile Dental Clinics and Robotic Units

Mechatronic Principle: combining diagnostic sensors, power-managed systems, and mobile platforms. In rural or isolated locations, mobile dentistry vans furnished with mechatronic chairs, sterilisers, and portable radiography machines offer complete care while enhancing accessibility.[41]

d) Smart Toothbrushes and Preventive Devices

Mechatronic Principle: Bluetooth connectivity, gyroscopes, and pressure sensors. In order to promote preventive oral health at scale, devices such as AI-powered toothbrushes (like the Oral-B Genius X) gather user brushing data and offer tailored feedback via mobile apps. [42]

e) Epidemiological Data Collection Devices

Mechatronic Principle: survey systems with biosensors and digital health kiosks. Integrated cameras and sensors are used by mechatronic dentistry kiosks to conduct oral health surveys and self-screens, sending data in real time to public health databases. By utilising tele-diagnostics, mobile care units, and AI-integrated data platforms, mechatronics improves community outreach in public health dentistry. Mechatronics is a key component that supports accuracy, equity, and efficiency in the delivery of oral healthcare as dentistry continues to advance into the digital era.[43]

CONCLUSION

Clinical practice and patient care have advanced significantly with the use of mechatronic principles in dentistry. More accuracy, automation, and customisation are now possible in all dental specialities because to mechatronics, which combines mechanical systems, electronics, control engineering, and intelligent software. The future of oral healthcare is being reshaped by mechatronics, from improved diagnostic tools and digital workflows in prosthodontics and orthodontics to robotic help in surgery and AI-driven data systems in public health dentistry. In addition to increasing treatment effectiveness and results, these developments also make dental care more widely available, less invasive, and more patient friendly. Mechatronics will play a more and bigger part in providing safer, more intelligent, and more environmentally friendly dental treatment as technology develops.

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