Making@Clinics

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Executive summary

The *Making@Clinics* project explores the integration of advanced digital fabrication technologies, particularly 3D printing, into clinical environments to enable on-demand production of patient-specific devices. While applicable to diverse healthcare solutions such as hearing aids or orthotics, the project's main case study focuses on sensor-equipped orthodontic aligners. These smart aligners enhance personalization, monitor wear compliance, and help prevent dental damage. The overarching goal is to develop compact "3D printing corners" that merge cutting-edge technologies with structural sensing, giving healthcare professionals *direct control over design and production*.

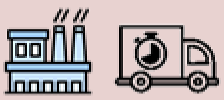
A key innovation is the **modular 3D printing corner**, which integrates 3D scanning, DLP-based (Digital Light Processing) additive manufacturing, automated pick-and-place robotics, computer vision for precision, and embedded sensors. A full digital twin developed in MATLAB/Simulink models the entire workflow, from printing and post-processing to sensor integration, enabling seamless transfer to real-world setups. Torque-control algorithms and PID (Proportional-Integral-Derivative) regulators coordinate process steps, while vision systems assist robotic handling.

The most innovative case study focuses on the realization of the **first dental aligners enhanced with battery-free pressure sensors**, which are manufactured with **PEDOT:PSS** (Poly(3,4-ethylenedioxythiophene):Poly(styrenesulfonate)) [1], a biocompatible and flexible conductive polymer. These cutting-edge sensors monitor in real-time how teeth interact with the aligner, providing a measurable and accurate indication to the patient of when replacement of the aligner is needed. The sensors are assembled on a polyimide PCB (Printed Circuit Board), and the system is encapsulated with **Parylene-C**, resulting in an electrically insulating coating layer that guarantees safety and stability [2]. Integration between PCB and aligner leverages silicone pads, microfluidic dispensing units for adhesive glues and UV-curable resins, and CNC (Computer Numerical Control)-assisted robotic placement.

Preliminary results include accurate aligner tracking with a **YOLOv8n neural network** [3], demonstration of automated workflows in the **digital twin**, and design of highly-sensitive and flexible **sensor prototypes**. The **PCB** for sensor data extraction has been developed, and the **control software** for data processing was implemented on Arduino, a prototyping platform for microcontrollers. This successfully enabled communication between the system and a smartphone via **NFC** (Near Field Communication), allowing wireless, battery-free data transfer [4].

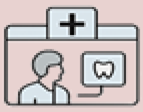
The project holds transformative potential for personalized, decentralized healthcare manufacturing. Key challenges include ensuring sterility, robust system integration, and clinical validation [5]. Future efforts will finalize PCB printing, sensors fabrication, refine real-time sensing feedback, and conduct early validation in clinical settings. Ultimately, *Making@Clinics* offers a blueprint for embedding Industry 4.0 principles into healthcare, enabling faster, adaptive, and sensor-driven patient care.

The problem



Centralized production and lack of personalization in orthodontic care, leading to delays, inefficiencies, and limited adaptability.

The challenge



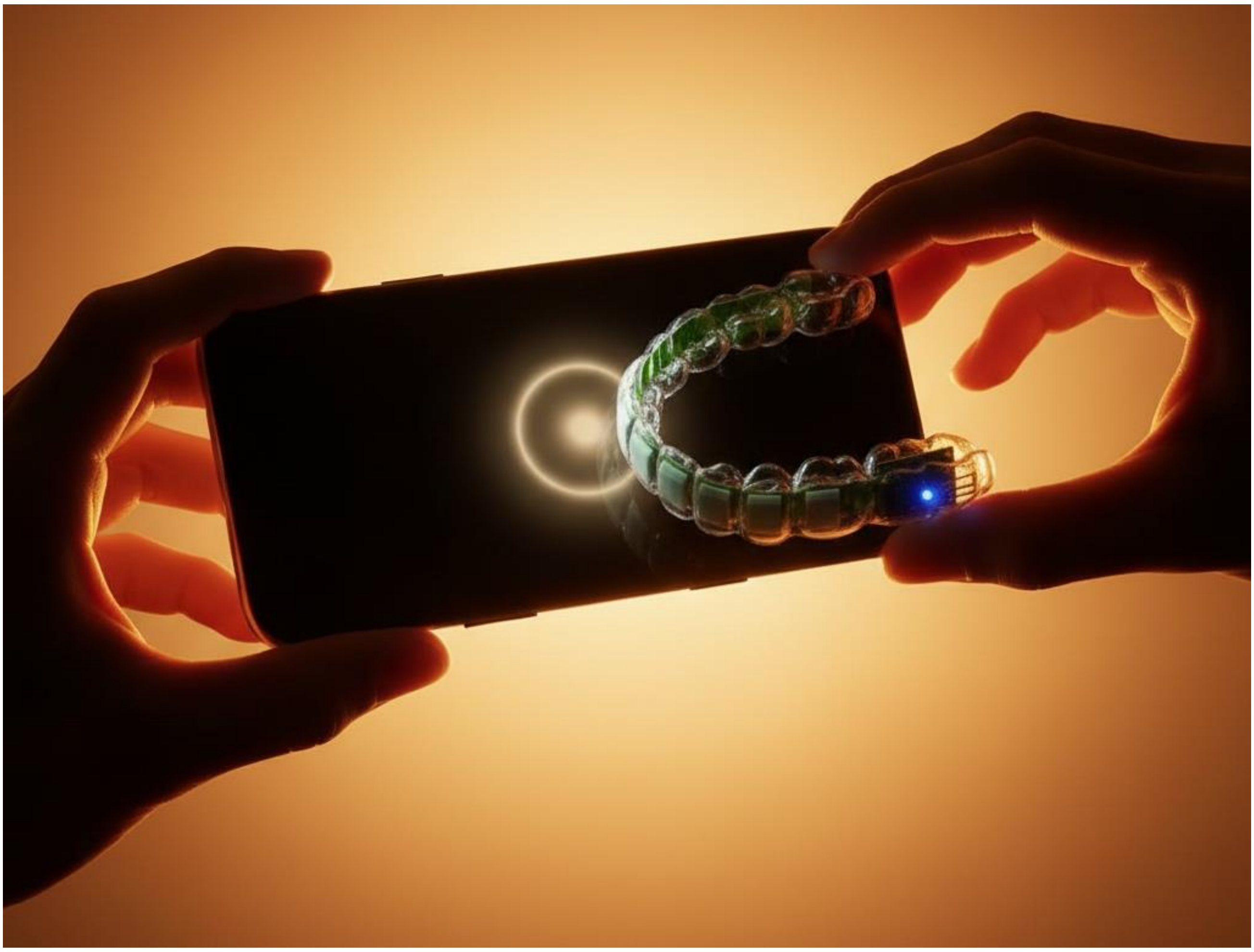
Designing a compact in-clinic corner that ensures industrial-grade quality while remaining manageable by clinical staff.

The goal

Fully automated production of sensor-equipped aligners, enabling dynamic, feedback-informed, and patient-specific treatments.

Key words

Automation, Orthodontics, Personalization, Smart Devices, Decentralization

Project description written by the Principal Academic Tutor

Making@Clinics aims to design and implement a compact, clean, and automated "Lab in a Corner" within clinical environments for the on-demand production of personalized medical devices. The project leverages advances in additive manufacturing (3D printing), materials engineering, and automation technologies to enable the rapid and safe fabrication of tailored biomedical solutions directly at the point of care.

The objective is to transfer the capabilities of a manufacturing hub into a scaled-down, clinically compliant setting, where healthcare professionals can access advanced production tools without the need for large centralized facilities. By integrating smart material processing, advanced 3D printing and automated workflows, with clean design principles, the Making@Clinics corner supports the creation of customized devices, patient-specific products such as clear dental aligners and digital hearing aids, while ensuring high standards of safety, reproducibility, and regulatory compliance.

Ultimately, Making@Clinics envisions a new paradigm of personalized medicine manufacturing, reducing lead times, optimizing costs, and empowering clinicians to deliver more effective, patient-centered care. This approach bridges the gap between engineering innovation and clinical application, bringing the lab-to-clinic transition closer to reality.

Team description by skill

The project required a multidisciplinary approach, leading to a subdivision of tasks that allowed each team member to contribute according to their expertise, while in some cases also developing new skills. The work was carried out as a team, with continuous collaboration across different stages of the project, while the more technical components were divided among members according to their specific backgrounds and responsibilities.

Fausto Allegrini designed custom-engineered components as uv cover lifter, washer machine, unit for detaching the aligner from its supports with cad modelling, defined Control strategy for all the components in the corner, simulated and tested digitally the full process.

Edoardo Bargis focused on the coating of the PCB. In particular, he worked on defining suitable materials, determining the parameters of the coating layer.

Gregorio Bergamo was charged with the development of the Computer Vision support system for aligners identification and gripping point triangulation starting from manual video labeling, to neural network training and validation.

Beatrice Losa contributed to manual video labelling and developed a COMSOL simulation of the sensor. She mainly focused on designing the PCB encapsulation process and entirely delineate its integration within the dental aligner.

Sofia Re and **Elena Stecconi** collaborated in originating and shaping the concept of integrating pressure sensing technology into the dental aligner. They oversaw the complete sensor design process, from material selection to fabrication, including parameter optimization for their realization.

Sofia Re took full ownership of the PCB design, from architecture and component selection to layout and datasheet compliance for seamless integration within the aligner. Beyond the technical work, she served as team controller and managed different stages of the project pipeline.

Elena Stecconi additionally developed the Arduino-based software required for programming the PCB's microcontroller unit, enabling NFC communication and processing of the sensor output data.

Goal

The primary objective of this project is to design a **fully automated, in-clinic system** that is clean, efficient, and user-friendly. Starting from a digital intra-oral scan, the system will deliver the final dental aligner directly within the clinic, minimizing reliance on external suppliers. By shifting production closer to the patient, the project aims to **reduce** transportation **costs**, **shorten production times**, and increase the degree of **customization** available for each case.

A central ambition is to introduce a significant advance in **personalization of orthodontic treatments**. The vision is to transform aligners into smart, high-tech devices capable of moving orthodontic care beyond static, prescriptive plans toward dynamic, feedback-informed interventions. Unlike the traditional “one-size-fits-all” approach, this personalized model allows for greater precision in therapy planning and execution, ultimately improving clinical outcomes.

In summary, this project seeks to **decentralize and modernize the production of dental aligners**, establishing a more efficient, cost-effective, and **personalized model** for orthodontic treatment.

Understanding the Problem

The current model for producing dental aligners relies on **centralized manufacturing facilities**, often run by third-party companies far from the point of care. While effective for large-scale production, this system introduces significant drawbacks: complex logistics and transportation increase costs and delivery times, leading to delays that affect both patients and clinical workflow.
A further limitation is the **rigid process** in which all aligners for a treatment plan are fabricated upfront, based solely on the initial scan and predicted tooth movement [6]. Patients are constrained to follow a **fixed replacement schedule**, typically replacing the aligner every two weeks with a pre-fabricated set. However, since orthodontic treatments span several months, biological variability, patient compliance, or complications can alter the expected progression. In such cases, pre-manufactured aligners and **standardized**, fixed **period for replacing the aligner** may no longer fit, forcing clinics to discard unused sets and restart production — generating **inefficiencies, added expenses, and reduced clinical flexibility** [7]. Moreover, this rigidity prevents real-time adjustments: any modification requires sending new scans to the central manufacturer and waiting for another shipment, restricting the clinician’s ability to respond dynamically. Such a workflow **contrasts with the principles of adaptive and personalized medicine**.

Addressing these limitations through in-clinic aligner production introduces additional challenges. Unlike centralized industrial facilities, the clinical environment must comply with **strict sterility and contamination-control standards** [5], which are difficult to maintain consistently when integrating manufacturing equipment into dental practices. This implies the need for controlled environments, specialized equipment, and rigorous protocols to ensure that aligners produced on-site meet **medical-grade quality requirements**. In addition, deploying a fully automated production system within the clinic raises critical concerns regarding **reliability** and **risk management**. While automation reduces human intervention, it also increases the possibility of improper use or interference by individuals not specifically trained for maintenance or operation. For these reasons, ensuring **robustness,** and most importantly **safety** is a prerequisite for the viability of any decentralized aligner manufacturing model. Without robust solutions to these challenges, the transition from centralized to in-clinic production could compromise both clinical outcomes and patient well-being.

Exploring the Opportunities

The concept of **in-clinic aligner production** is not new as some clinics already implement it using **thermoforming** technique. In this method, clinicians perform an intraoral scan, export a treatment plan via CAD software, then 3D-print physical dental models and thermoform plastic aligner sheets over them [6]. For example, Bellevue Orthodontics [8] offers clear aligners same-day to patients using this workflow.

Providers like Forestadent [9] promote in-house thermoforming using PETG or polyurethane sheets over printed model.

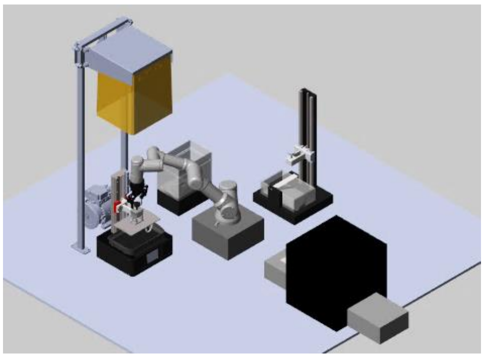
This method lowers costs and enables more responsive treatment adjustments, but it still involves multiple manual steps—as model printing, manual trimming and polishing—introducing potential error and labor intensity [7]. Thermoforming is reliable and relatively low-cost, but **its precision is limited**.

Ongoing research in orthodontics is exploring the integration of sensors to enhance treatment, with particular attention to **materials** (such as flexible sensing polymers), **biocompatibility** (through functional coatings), **data reliability**, and the development of **battery-free, wireless solutions**. To the best of our knowledge, however, such sensors have so far been designed primarily to monitor **pH, temperature, and specific chemical compounds** [10].

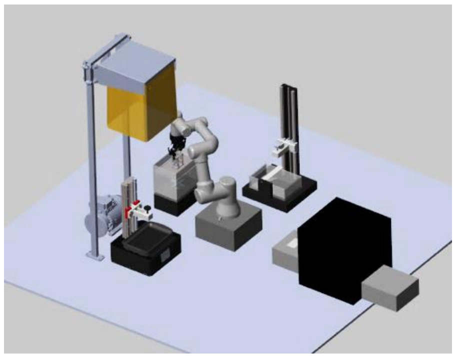
On a different page, **Digital Twin** (DT) has emerged as a cornerstone of industry 4.0. It can be defined as a virtual representation of a system, that is updated with data from the real world, enabling bidirectional synchronization between the physical and digital domains. It is standardized by ISO 23247 [11]. It is extremely useful for **testing systems without** the risk of **damaging** real components. Moreover, **Computer Vision** enhanced by Neural Network proved its utility in many context, specifically for visual sensing and returning visual feedbacks.

Generating a Solution

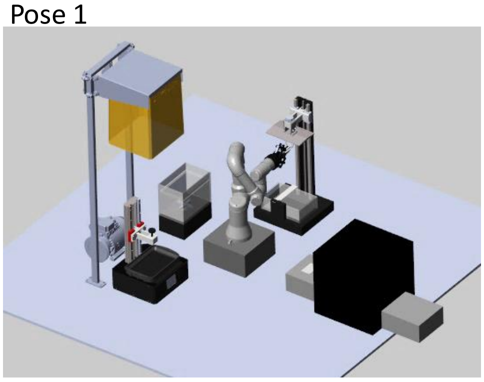
The solution developed in this project involves the creation of dedicated "**corners**" within individual dental clinics. A corner is a compact, modular systems composed of multiple interconnected processing stations, designed to fully automate the production of dental aligners — from an intra-oral digital scan to a final product.



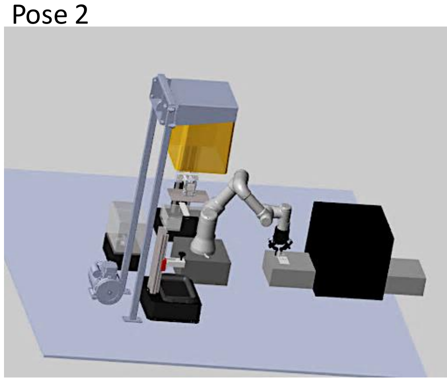
Pose 1



Pose 2



Pose 3



Pose 4

Fig. 1 Schematization of the main poses of the robot for the transitioning of the aligner in the different stations of the corner

A high-resolution **3D printer** fabricates aligners via **UV-induced** polymerization of a specialized bio-medical resin, ensuring both geometric precision and consistent material properties [7]. After printing, the aligners go through a series of automated post-processing steps shown in Fig 1. pose 2. These include cleaning and UV post-curing. After post-processing, the aligner is detached from its support (pose 3) and positioned on the conveyor to enter inside the last station (pose 4): a machine for inserting the sensor inside each aligner (outlined in next section).

The **transition of aligners** between processing stations is handled by a **robotic arm** controlled by Computed Torque Control. The corner is integrated with two RGB (Red Green Blue)-depth cameras which enable the development of a Computer Vision algorithm to sense the aligner position in the space at every time instant. This setup enables a fully autonomous workflow, minimizing manual intervention while maximizing consistency, reliability, and repeatability throughout the production process.

The next step of the dental aligner production chain is the **fabrication of battery-free pressure sensors**, shown in Fig. 2. They are manufactured with **PEDOT:PSS** [1], a ***biocompatible*** and ***flexible*** conductive polymer. To ensure user comfort, these devices are realized through advanced techniques such as screen printing on microstructured **PDMS** (Polydimethylsiloxane), creating ***extremely thin*** sensing layers. These pressure sensors can measure the forces exchanged between the aligner and the patient's teeth during use. This functionality is crucial for ***maximizing treatment personalization***, as it allows clinicians to verify whether an aligner remains effective, needs replacement, or is exerting potentially harmful pressure.

The sensors are mounted on a polyimide flexible **PCB** (Printed Circuit Board), which is essential both for extracting pressure data and for enabling wireless communication with a smartphone via **NFC** [4]. Through a dedicated **smartphone application**, patients and clinicians can directly access real-time information about the dental aligner and its impact on the teeth.

The PCB is encapsuled with **Parylene-C** [12] using Chemical Vapor Deposition technique, creating a transparent and electrically insulating coating layer to guarantee device reliability and patient safety [2]. The PCB integration onto the aligner employs robotic arms for handling **silicone pads** and uses microfluidic dispensing systems to apply **cyanoacrylate adhesives** and **UV-curable resins**. Precise and consistent sensor-aligner positioning is ensured with a **CNC platform** equipped with a **customized vacuum plate**.

The end product of the workflow is a **dental aligner integrated with flexible electronic components**, as the one shown in Fig. 3.

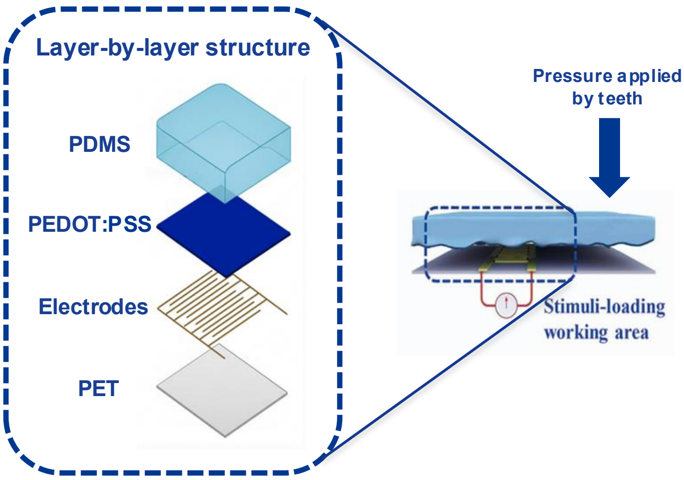


Fig. 2 battery-free pressure sensor for dental aligners, with a zoom on the layer-by-layer structure of the stimuli-loading working area. The image illustrates where pressure is applied by the teeth and how the underlying structure detects the signal through electrodes [8].

Fig. 3 Sensorized Dental Aligner: the integrated PCB is shown in green and the pressure sensors in light blue. The electronic components are ultra-thin and flexible, conforming seamlessly to the aligner's shape without compromising fit or comfort.

By bringing production directly into the clinic, this system overcomes the limitations of traditional centralized manufacturing while enabling **truly personalized orthodontic care**. It eliminates delays and logistical complexities associated with shipping pre-fabricated aligners from third-party facilities, ensures a controlled and sterile environment suitable for clinical use, and incorporates automated safeguards to prevent errors or unauthorized handling. At the same time, real-time sensor feedback allows clinicians to **continuously monitor treatment progress** and **adjust aligners dynamically**, addressing the lack of adaptability and personalization inherent in fixed-schedule, pre-manufactured systems. In this way, the approach combines the efficiency of automated, on-site production with the flexibility needed for patient-specific, adaptive treatments, **improving both operational workflow and clinical outcomes**.

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