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A VIRTUAL REALITY INPUT DEVICE FOR SPORTS-RELATED REHABILITATION

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ABSTRACT

This work entails the hardware design, manufacturing and implementation of a VR controller device tailored for people with specific sports-related injuries. The target case of this thesis is the tennis elbow injury, where the designed controller helps them interface easily to the VR environment that is designed for their therapy.

The sensors used are carefully selected in order to adequately capture the therapy exercise movements related to this kind of injury. For example, the use FSRs (Force Sensitive Resistors) that are put on the surface of a test object helps to detect a grasp during the exercise.

The hardware design and manufacturing was done for a VR controller device that would give the desired performance, using Arduino IDE for its software development. In addition to this, the design of the VR environment allowed for an immersive VR experience for the rehabilitation.

An experiment was carried out with eight participants, where they were asked to perform two exercises that involve grasping the test object. A series of questions were asked to them as part of the experimental evaluation. The results showed positive indications about the participants' experience.

Keywords: VR, Force Sensitive Resistor, Arduino, controller, upper limb rehabilitation, tennis elbow, virtual environment

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FOREWORD

This work was done as part of the ongoing research of the Center for Ubiquitous Computing at the University of Oulu. I would like to exceptionally thank Assoc. Prof. Georgi V. Georgiev, Yazan A.M. Barhoush and Dr. Vijayakumar Nanjappan for their continued support and supervision at all the stages of this research. Lastly, I would like to thank my family and friends for their support and encouragement.

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LIST OF ABBREVIATIONS AND SYMBOLS

3D	Three Dimensional
CAM	Computer Aided Manufacturing
DOF	Degree of Freedom
ECG	Electrocardiogram
EMG	Electromyography
FMG	Force Myography
FSR	Force Sensitive Resistors
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
LDA	Linear Discriminant Analysis
LED	Light Emitting Diode
MMG	Mechanomyography
NIRS	Near InfraRed Spectroscopy
PC	Personal Computer
PCB	Printed Circuit Board
RMS	Root Mean Square
ROM	Range of Motion
SPI	Serial Peripheral Interface
SQL	Structured Query Language
SVM	Support Vector Machine
sEMG	Surface Electromyograpghy
TLX	Task Load Index
UV	Ultra Violet
VR	Virtual Reality
WBAN	Wireless Body Area Network

1. INTRODUCTION

Physical activity through sports is done extensively throughout the world. For a healthy life, it is advisable to strive for at least a couple of hours of physical activity every week. Even so, this path for well-being also comes with shortcomings in case of injuries. There are several sports-related injuries, with the focus of this thesis being on the tennis elbow injury.

Lateral epicondylitis, commonly known as tennis elbow, is a condition that results from intense physical activity, which causes strain to the tendon involved in wrist movement. The strained tendons cause pain and discomfort for a tennis elbow patient, especially when there's an activity using the elbow and wrist area muscles. This condition is the most observed among people with elbow injuries[1] and, in the United States, its prevalence is about three percent annually. As the name suggests, tennis elbow patients can come from certain sports like tennis, badminton, and other physical exercises that could cause strain to the tendon due to excessive use of elbow and wrist muscles.

Although several treatment methods are available for tennis elbow, there isn't one that's completely reliable[2]. Therefore, research is ongoing in this field and, several treatment options have been explored and evaluated. Among these, we have non-surgical and surgical approaches. Surgical treatment is done in the worst cases and is advisable after the non-surgical treatments have not been effective for over 6 to 12 months. Non-surgical treatment is the most commonly used approach when it comes to tennis elbow, and it encompasses a lot of variations depending on the method used and the severity of the condition. It could vary from a simple restraint to continuing the causal physical activity or, even better, exercises that aim to make the condition better. The latter is commonly accessed through therapy with a professional trainer or physician and has proved to be very useful over the years. However, several questions need to be raised nowadays, and to name a few there could be a problem with the cost-effectiveness of the therapy in case of limited budget patients or ease of movement to the therapy location in case of the elderly, even more significant these days, is the need for self-distancing because of the pandemic. For these reasons, recent advancements in technology have allowed the development of devices that deal with some of the limitations of in-contact therapy by making it easy for the patient to carry out the treatment independently.

Generally, all these technological developments have a few things in common. First, they employ sensors designed to detect several parameters of the patient, such as the wrist's angle of inclination and muscle tension. Next, many solutions employ actuation as a form of movable handles for the wrist's workout. Another interesting solution and which will later be the subject of this thesis, is to put the patient in a VR environment where the games played are tailored to the physical therapy of the patient.

The work carried out in this thesis is to design and manufacture VR controller hardware designed to help in the rehabilitation of the tennis elbow condition. The developed hardware can later be programmed to interface to a VR environment intended for the therapy. The type of therapy desired for this application involves squeezing a bottle. For that reason, sensing is very critical to be able to track these

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[1] https://www.ncbi.nlm.nih.gov/books/NBK431092/

[2] https://www.sciencedirect.com/science/article/abs/pii/S2468122921000463

movements in the environment; a series of Force-Sensitive Resistors (FSRs) are put on the surface of a test object (plastic water bottle) to be able to detect a grab. Moreover, these signals and data need to be sent to the PC to be accessed by the VR environment. The Bluetooth interface satisfies these requirements.

After exploring recent work in this direction, several insights were acquired regarding the best hardware to use to suit rehabilitation requirements for tennis elbow. A detailed discussion of previous work will be discussed in the next chapter. Most importantly, the choice of the sensors was based on the types of movements in the physical therapy and how best to replicate these in the VR environment. Such an environment requires well-suited sensors to detect these movements. Sensing the wrist was an important consideration. The FSR was the best sensor suited for this as it detects the slightest muscle movements required for accurately modelling the patient's wrist. For additional exercises, the elbow can also be exercised to provide versatility to the therapy. The elbow could be detected by using an Inertial Measurement Unit (IMU) because its flexibility and length give it more degrees of freedom. Although elbow sensing is reviewed in this literature, it is not implemented as part of this study.

2. LITERATURE REVIEW

This section gives a brief overview of the work done about the topic of focus for this thesis. Mainly, the review is centered on rehabilitation hardware. Since the particular case of tennis elbow closely resembles other wrist and arm rehabilitation strategies, the review was chosen targeting similar conditions and, therefore, not limited to tennis elbow. As introduced before, tennis elbow rehabilitation requires careful choice of sensors for the wrist and a systematic approach that uses the sensor data to tailor the rehabilitation accordingly. For that reason, the review has two parts.

First, it explores previous work on efficient sensors for the wrist; in this, different sensors that use various technologies are explored, and for each work, the working principle and accuracy are reviewed. For each work that introduces a new sensor, its working principle is first explained so that the analysis makes more sense and is enjoyable. Assessment of the Majority of the work explored is simply reviewing the accuracy of a particular sensor at recognizing a range of hand gestures. Some studies were presented, from which two different sensors are compared by analyzing how well they fare against each other at recognizing hand gestures. These comparisons are beneficial as they highlight some of the advantages and drawbacks of some sensors.

The second part of the literature review dives deep into the rehabilitation done using the previously mentioned sensors. This part describes the different techniques used for rehabilitation through wrist exercises. The methodologies in this review are diverse and employ creative approaches that range from actuation, VR, telerehabilitation, and more. The assessment of the technique is done by reporting the respective work's patient feedback, increase in ROM (Range of Motion) of the subjects as well as the accuracy at exercising critical points in the rehabilitation. All this information is obtained primarily from the muscle activity reported by the sensors.

2.1. Wrist and Elbow Sensors

2.1.1. Wrist-Sensing Wearable Device for Gesture Recognition

Liang and colleagues at the University of Glasgow developed an interesting wrist-sensing wearable device for gesture recognition. Their study [1] revolves around the principle that every hand gesture is associated with tendon movement. Therefore, being able to record and analyze the pressure distribution around the wrist would give a sense of which gesture was performed. This necessitated the use of capacitive pressure sensors distributed around the wrist and wrapped around by a band.

The working principle is straightforward, the pressure exerted on the sensor makes a capacitance value change and, these capacitance variations around the band can be processed using an algorithm to predict the causing gesture. The algorithm uses Support Vector Machine (SVM)[3], a machine learning technique that is suitable for pattern recognition because of its flexibility to work with fewer samples.

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[3] https://www.sciencedirect.com/topics/neuroscience/support-vector-machine

Despite specific noise sources, such as the human body's inherent capacitance that introduces imperfections, The system claims to reach a 90% accuracy, which would certainly make it a useful and reliable wrist sensing option.

2.1.2. Wrist Sensing Using EMG and FSR Sensors

Another study conducted by McIntosh and Colleagues at the University of Bristol [2] came up with a combination of Electromyography (EMG) and Force Sensitive Resistor (FSR) sensors to improve the accuracy of the wrist sensing system and hence provide better gesture prediction.

When a hand gesture is performed, the contraction of the muscles gives rise to an electrical potential difference between EMG electrodes placed around the surface of the arm; a total of 8 electrodes has been studied [3] to give the best results. In addition, the pressure generated by tendons around the wrist area causes a change in the resistance of FSRs that are placed around the wrist. All these sensor data are then fused by a machine learning algorithm [2]to recognize the gesture involved.

Twelve participants wore the FSR sensor on the left wrist and the EMG electrodes on the arm. They were asked to perform 15 different gestures (5 wrist, 5 fingers and 4 hand gestures), 10 times per gesture. The results of the study claim a considerably high accuracy of 96% and a faithful detection of a wide range of gestures. The strategic placement of the FSR sensors on the wrist and EMG sensors on the arm is the main contributor. They explain that a gesture typically involves the activity of muscle/tendons in the wrist and arm area, making sensing of both areas more advantageous. This puts to question the conventional sensing that only focuses on wearables placed only on the wrist.

2.1.3. Sensing with a 9 DOF Digital Sensor

A different approach by Sarcevic et al. [4] where a 9 DOF digital sensor comprised of gyroscope, accelerometer, and magnetometer was used. Here, the main goal was to use a wrist-mounted device that can help predict different arm movements and activities.

Two sensors are attached, one on each wrist of the 9 chosen subjects, then asked to perform 11 activities such as raising/lowering arms, jogging, walking and stationary positions. Data from both sensors is first preprocessed to extract specific features, and then a radio transceiver sends it to the central processing station, where classification takes place to find out the activities/movements involved. The efficiency reached by this method promises 90% accuracy by using 800 ms window size for the data sets and when the data from the three sensors are used together.

2.1.4. Review of Myo Armband and Leap Motion Controller

In this study, a game is proposed for a human to computer interface [5], by reviewing the performance of two commercial wrist sensors namely, Leap motion controller and

Myo armband. The review is based on their ability to detect the five basic wrist movements: extension, flexion, pronation, supination and neutral.

The Leap motion controller[4] uses two infrared cameras and 3 LEDs to capture the hand movements. The next one is the Myo band[5] which uses 8 sets of EMG electrodes to sense the electrical activity of the muscles (gestures are associated with muscle activity) and one IMU to detect the motion of the arm.

The evaluation for the Leap Motion controller was performed by collecting Hand orientation as well as the position of the wrist, elbow, proximal phalanx of the index finger for all the 5 basic wrist movements. The angle between the proximal phalanx and the elbow is computed for all the cases and compared to known values of it for all the cases. On the other hand, the Myo band's evaluation, for wrist movements involving spreading out or in of the fingers are identified using the EMG electrodes signals and the movements requiring rotation of the wrist are Obtained from the IMU, where the roll angle is computed and compared to known values of it for the basic movements. Finally, 8 participants performed the five movements on each of the sensors. The data was recorded based on correct and wrong predictions, and scores are given in terms of accuracy, sensitivity, and specificity. Despite some differences in detection for some movements, all the sensors were able to perform well with an average of 85% accuracy.

2.1.5. IMU for Measurement of Wrist and Elbow's ROM

A couple of researchers from different Universities of Spain did a study to identify the trustworthiness of an inertial sensor(IMU) in the measurement of Range of Motion (ROM) for the elbow and wrist [6]. They compared the results of the inertial sensor against those of a goniometer which is the conventional and commonly used tool for measuring ROM.

For the study, ROM was measured on participants who did the basic movements of the elbow (flexion, extension, pronation, and supination) and wrist (flexion, extension, lateral deviation, and circumduction). All these measurements were done using both the IMU and the goniometer. The assessment was done by two different physiotherapists, and their observations were recorded. Finally, the results of the study confirmed that the IMU is a reliable digital measurement alternative to the goniometer as it recorded a 3° maximum difference for the elbow and 1° for the wrist.

2.1.6. EMG Sensors and Accelerometers for Accurate Gesture Detection

Different experimentation on combinations of sensors have been explored. One example [7] is where a study was done to identify the effectiveness of using EMG sensors coupled with accelerometers at detecting hand gestures accurately.

A DELSYS Myo IV was used for signal analysis with 2 Accelerometers and 2 sEMG (Surface Electromyography) sensors. In the experiment, participants had the 2 Accelerometers attached one at the back of the hand and the other on the

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[4] https://www.ultraleap.com/product/leap-motion-controller/

[5] https://developerblog.myo.com/

arm near the wrist arm joint. The sEMGs were put on the arm. The participants were asked to perform a class of 24 hand gestures divided into four parts(wrist motions, finger motions, and multi-finger motions). After data acquisition, a signal segmentation algorithm is used to identify parts of the signal that corresponds to gesture actions. Next, feature extraction is done to find the different gesture classes. Finally, classification is done to identify individual gestures. The results showed that when all the sensors are used together an accuracy of 97.8 is reached. This is 5-10% more than if sEMGs are used alone.

2.1.7. Combination EMG and FMG Sensors for Better Accuracy

Nowak and colleagues at the Institute of Robotics and Mechatronics, (DLR) experimented with a combination of sEMG and FMG sensors [8] for better accuracy at detecting hand gestures. The study was done to improve the efficacy of the upper_limb prosthesis. FMG (Force Myography) signals according to Connan et al. [9] can be recorded by using FSRs.

In the experiment [8] 10 FMG and 10 sEMG sensors were put in a bracelet and placed around the forearm. The participants were asked to perform 5 hand movements (power grasp, flexion, extension, supination, and pronation) 5 times. A regression-based machine learning algorithm was used in the identification, and results were based on a ratio of successful tasks overall tasks(SR). The results showed that using values FMG alone gave an SR of 83.3% and sEMG alone gave a poor 33%, a mixture of the sensors in stacked combination gave a 73.33%.

2.1.8. MMG Sensors for Hand Gesture Detection

Another kind of sensing approach discussed here [10], is the use of MMG (Mechanomyography), which is the sensing of muscles' mechanical activity to identify the gestures.

A TSD250A VMG Transducer[6] is a sensitive accelerometer used to record vibrations associated with muscle contraction and retraction. An MP160[7] is used for data acquisition and analysis. For the experiment, 8 participants had 4 VMG sensors attached to the critical muscles for detection and were asked to perform 3 hand gestures (Grip strength supinated, Flexion fingers, Pinch grip) 5 times. After processing and classification with Linear Discriminant Analysis (LDA) for pattern identification, an accuracy of 87.5% was recorded.

2.1.9. NIRS and EMG Sensors for Hand Movement Recognition

The results of this study are based on the use of NIRS (Near InfraRed Spectroscopy) and sEMG for hand movement recognition [11]. NIRS is the use of nearinfrared radiation to deduce the level of oxygen in tissue. By measuring transmitted and

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[6] https://www.biopac.com/product/vibromyography-transducers/

[7] https://www.biopac.com/product-category/research/systems/mp150-starter-systems/

reflected radiation, such information can be extracted. This principle forms the basis for muscle activity detection because when muscles are contracted they need more oxygen in the tissues and hence draw more blood than when relaxed [12].

In the implementation [11] two devices were used. PortaMon[8] which is an NIRS system and Trentadue[9] for EMG signals. These two devices were placed on 8 subjects who performed 3 hand rest, finger extension, and wrist extension twice for each of the chosen 3 varying force levels. The results after classification showed that NIRS showed an accuracy of 74.5% to identify the force exerted in the movements and also a 92.2% accuracy for a combination of NIRS and EMG sensors for movement identification.

2.1.10. Barometric Pressure Sensors for Gesture Detection

These researches used barometric pressure sensors [13] to detect hand and finger movements. The principle is that muscle activity (contraction and relaxation) also influences air pressure [14].

The results for the study [13] were obtained after 10 participants were fitted with a wrist band containing 10 barometric pressure sensors around the arm. These subjects were asked to perform 6 Wrist gestures, 5 Finger gestures, and 10 Chinese number gestures. The sensor data was captured by an Arduino module and serially send to the desktop where a classification algorithm was running. After accuracy calculation, it was seen that a 98.1% accuracy for wrist gestures, 94.4% for finger gestures, and 90.0% for Chinese number gestures was achieved.

2.1.11. FSR for Static and Dynamic Hand Gestures Detection

The study's objective was to use pressure sensors to accurately recognize hand gestures [15]. Pressure signals can be detected in many ways, however, for this study, an FSR-based design was used.

The hardware setup consisted of a wrist band of 4 FSR sensors, a multiplexer for sampling the FSR sensors, and an MSP430FR5969 microcontroller for processing. In the experimentation, 10 participants, of which 5 were experienced users. These participants performed a total of 5 static hand gestures and 3 dynamic hand gestures for 2 minutes. After classification, results showed that for a 100ms delay in gesture recognition, an accuracy of 95.28% was achieved.

2.1.12. FMG Vs EMG Sensors at Hand Gesture Detection

Another study involving FMG and sEMG sensors was carried out here [16]. The main objective of the study was to compare the effectiveness of FMG against sEMG sensors by measuring how accurate they are at recognizing a set of gestures. FMG sensors in this experiment are also implemented using FSR.

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[8] https://www.artinis.com/portamon

[9] https://www.otbioelettronica.it/en/products/legacy-device/item/112-trentadue-en

Table 1. Summary of sensors and body parts sensed

[HTML]000000Authors	FMG(Piezocapacitive)	FMG(FSR)	EMG	IMU	Myo Arm Band	Leap Motion Controller	Accelerometer	MMG	NIRS	Barometric Pressure Sensor
Liang et al.[1]	Wrist and Fingers									
Mcintosh et al.[2]		Wrist	Fingers							
Sarcevic et al.[4]				Arm and Body						
Rechy-Ramirez et al.[5]					Wrist	Wrist				
Costa et al.[6]				Wrist and Elbow						
Chen et al.[7]			Wrist and Fingers				Wrist and Fingers			
Nowak et al.[8]		Wrist and Fingers	Wrist and Fingers							
Ismail et al.[10]								Fingers		
Paleari et al.[11]			Wrist and Fingers						Wrist and Fingers	
Shull et al.[13]										Wrist and Fingers
Zhang et al.[15]		Wrist and Fingers								
Jiang et al.[16]		Wrist and Fingers	Wrist and Fingers							

The two hardware setups include an FSR band that has 16 FSR sensors and an acquisition module. The second setup consists of a Myosystem 1400 L acquisition system that is coupled to 8 sEMG sensors. In the experimentation 12 participants were fitted with both the FSR and sEMG sensors one on the wrist and the other on the arm (the setup was interchangeable), then the subjects were asked to perform a range of 48 gestures divided into 3 sets (16 grasp types, 16 sign language gestures, and 16 individual finger and hand movements). The gestures were performed 5 times by each of the subjects and the readings were recorded by the respective acquisition units. The results confirmed the FMG superiority over sEMG because an 8 sensors FMG setup recorded an accuracy of 91.2% compared to an 8 sensors sEMG setup which recorded 84.6%. Additionally, it was seen that increasing the FMG sensors to 16 increased the accuracy to 96.7%.

2.1.13. Summary on the Sensors Study

The careful exploration of various sensors gives an idea about the complexity, accuracy and efficiency to expect in the implementation. Table 1 summarizes the sensors that were reviewed and the parts that were sensed on the body. Depending on the application, the sensors chosen should be tailored to the types of gestures to be sensed. As showcased in numerous research reviews, FMG and EMG sensors appear to be the most commonly used, because of the extensive research done on them. Therefore, most of the fast prototyping applications use them.

Jiang et al. [16] gives an interesting comparison between FMG and EMG, and later draws a conclusion that FMG sensors were found superior in accuracy. Additionally, FMG sensors provide better accuracy as more sensors are incorporated into the design. Since the subject of this thesis relates to wrist pressure detection, an FMG sensor approach was followed by using FSRs.

2.2. Hardware Controllers for Rehabilitation

2.2.1. A Low Cost Wrist-Elbow Rehabilitation Device

Paul at the University of Utah developed a device aimed at rehabilitation of the wrist and elbow [17] and in particular for the tennis elbow condition. The main objectives of the design were to have a low-cost rehabilitation device and collect data that could be useful in subsequent research.

The device works by assisting the patient's wrist movement in performing wrist flexion and extension through a motor actuating the handle. The system mainly consists of a computer and a resistance device, where the computer produces a control voltage that adjusts the torque of a motor that is part of the resistance device. This provides a load to the handle as the patient goes through the flexion/extension wrist movements. The computer encompasses a user interface where the patient or professional can set the desired parameters based on the training goals and a Simulink interface that implements the control system for the design. Throughout the device operation, there are feedback signals that are fed to the Simulink interface, such as the angular velocity and torque extracted from the motor, the patient's muscle activity extracted from EMG electrodes fitted on the patient's arm, the pain level signaled by the patient by using an input pain button and lastly, a motion capture that's recorded by installed cameras. The angular speed and torque are adjusted for correctness in the control loop, whereas the pain level feedback is used to stop the movement when the desired behaviour is reached. Additionally, the EMG signals and motion capture are used to compare the device's behaviour to the known parameters of conventional loading schemes.

The final evaluation of the performance yielded good results, where the measured torque to desired torque showed an RMS error of 0.1 Nm for the maximum torque of 3 Nm applied. Moreover, the mean difference between the device loading and conventional practices was around 1cm.

2.2.2. Massage Therapy Device for Rehabilitation

In the study carried out by Chimsa et al. [18], a massage therapy device was developed for tennis elbow patients. The treatment is centred around the need for good blood circulation for the muscles in the elbow area. This can alleviate the pain associated with the sore tendons.

The device consists of bevel gears, one of which has a ball pressure that feeds to an armband of the patient. The bevel gears are moved by a servo motor which is computer-controlled using a microcontroller. The device has operating modes that depend on the required amount of pressure and time as well as a stop mode in case of discomfort. The pressure exerted by the device depends on the distance of the ball and skin.

The assessment of the device yielded a 100% accuracy for the distance between the ball and skin relative to the specifications and desired pressure in each mode. Although one of the test subjects reported a slight discomfort in one of the modes, the other subjects' experience was quite decent.

2.2.3. Exoskeleton System for Rehabilitation

A VR-based solution for the rehabilitation of tennis elbow or similar conditions was present in this study [19]. The developed device is an exoskeleton system that is worn and extends from the forearm up to the outer arm. This device assists in the rehabilitation of the patients by interfacing to a VR environment where exercises curated to the condition of the patient are done.

The device consists of 3D printed frame which is attached to the forearm and outside arm by 3 velcro straps, one on the forearm, the second on the elbow joint, and the third on the biceps area. The fore-arm and biceps area frames are joined together by a joint connected to a servo motor which assists the forearm movement. The forearm frame has a strain gauge whose resistance changes according to the force applied by the forearm, this is helpful for the servo motor to estimate the amount of torque required to lift the arm. This is very useful in case the user is lifting a weight, in which case the servo would offer extra assistance during the lifting. The whole system is connected to an ESP8266 microcontroller for processing and most importantly to use WiFi connectivity to communicate with the VR environment. The VR environment consists of exercises aimed at the rehabilitation of the patient, such as picking up an object and putting it on the table or moving a disk-like object through a carefully drawn curved line, from start to finish. There are a lot of interactive activities in the VR, and the patient is challenged and in the process rehabilitates faster. Additionally, the database offers critical data on the patient's activity and progress as well as data that could be very useful in the assessment of the patient's progress.

The final evaluation was performed, where there was a comparison between playing the VR game with a simulated weight by using Oculus VR accessories and one where there are real weights and the Exoskeleton assistance. After a couple of sessions, it was observed that the exercises performed with real weight showed more collisions than the simulated weight but in most cases, the discrepancy ameliorates as the patients get used to the game.

2.2.4. Portable Tracking Device for Hand and Arm Rehabilitation

Lalov and Manolova at the technical University of Sofia made a device whose main purpose is to track arm and hand which they implemented in such a way that it could be very useful for rehabilitation.

The device [20] consists of an IMU, Bluetooth module, and Arduino Micro-Pro for processing. The IMU provides acceleration and angular velocity data of the patient and they are filtered by a Kalman filter algorithm to account for the drift. The final filtered values are sent via Bluetooth to a smartphone where an Android app runs an algorithm that processes the patient's movement. Based on the ROM, pitch, and angular velocity the exercise is labeled as successful or not. Also, the data provided by the device could be evaluated by a professional to track the improvement of the patient. Moreover, the device is suitable for a range of conditions affecting tendons, muscles, and joints of the arm and wrist area. The results obtained from the experiment showed that the use of the Kalman filter drastically counteracted the bad effects of drift associated with IMUs, therefore the reliability of the device was also assured.

2.2.5. Therapeutic System for Wrist and Forearm

In this literature, a device was designed to assist in the rehabilitation of the wrist and forearm [21]. The work was targeted at elderly people but the techniques used apply for general rehabilitation. The system uses a steering handle used by the patients to play a game.

The device consists of an Arduino Uno for the processing, a rotary encoder to keep track of the arm position when the steering handle is moved. The data from the rotary encoder is sent to a PC via USB and the data is incorporated into Unity where the game is hosted. The game is designed such that the user performs 4 basic movements (extension/flexion and pronation/supination).

The evaluation of the device after 3 weeks of use increased the ROM of the users. This was showcased first by the patient's score increase after weeks of playing the game. Secondly, EMG sensors attached to the patients during the game showed muscle activity showed coverage of the 4 movements that were targeted. Last, a Goniometry measurement of the users shows that there was an increase in the ROM for the 4 tested movements.

2.2.6. Upper Limb Rehabilitation Using VR

Another rehabilitation system targeting the upper limb was studied here [22]. The design uses a VR-based system to help in the rehabilitation of the patients. It includes a hardware controller, a webcam, and a PC which hosts the VR software. The hardware controller is a gripper kind of design with a colored ball on top (used for tracking), the controller has a pressure sensor on it to make it easy to integrate with the VR environment. The tracking software of the VR system uses the pressure sensor values, along with the webcam data to track the hand and arm of the user. Games played in the environment make use of common therapy gestures. Examples are a game where the user needs to flip a steak while cooking and avoid burning it. The difficulty level of the game is continuously adjusted by an adaptation algorithm that communicates to the game engine.

The evaluation of the study brought together patients that were already receiving therapy, and with the guidance of the therapist, the study conducted on this group showed that this device was indeed useful for rehabilitation.

2.2.7. Wearable Sensors for Elbow Rehabilitation

Researchers at Busan and Xinxiang institutes developed a multi-sensor network [23] that could be used to collect critical data while the patient undergoes rehabilitation. The obtained data could be used by therapists to monitor and enhance the rehabilitation routine of the patient. The sensors consist of a motion sensor, EMG, ECG, and temperature sensors. These sensors work as part of a Wireless Body Area Network (WBAN) where they act as terminal nodes that communicate to a gateway node which connects them to a proximal system and later to a remote system for monitoring.

Each terminal node consists of a sensor (motion, ECG, EMG, or temperature), a data acquisition system (Interface, A/D conversion, and storage), a DSP for processing, and data transmission (Bluetooth) to communicate with the gateway node. Based on the motion data acquired from the gateway node a study was made to simulate a design of an exoskeleton robot that could help in the rehabilitation and act smoothly to avoid injuries. After completion of the study, the simulation proved to be successful with the exoskeleton assisting the rehabilitation and covering the Range of Motion (ROM) required. Furthermore, a thorough test of the individual terminal nodes as well as the network reliability proved to be successful and promising good performance for a real-time system.

2.2.8. Video Game Based Rehabilitation

A more interactive study here [24] describes the development of an EMG-based rehabilitation system that gives feedback to the user via a video game.

The setup consists of EMG electrodes mounted on the user's arm and connected to a custom processor board which relays the readings to a laptop via radio. On the laptop, a neural network algorithm is implemented to analyze the EMG electrode data of the patient's exercise and classify them according to preset gestures. Moreover, a video game is also developed in Java and allows the user to play rehabilitation-based games, and the video game monitors the patient's muscle activity by sending queries to the neural network about what kind of muscles the user is currently using. Then, based on that, the game rates the user's performance during the game.

A study was done to identify the effectiveness of the system by assessing its accuracy at classifying basic rehabilitation exercises. The results showed that an accuracy of 96% was achieved for a 2 exercises classification, 92% for 6 exercises, and 60% for 8 exercises.

2.2.9. Handheld Remote Controllers for Rehabilitation

Handheld remote controllers have attracted the attention of researchers. Particularly, in this study, an assessment was done on the Nintendo Wii's game controller as a good alternative for upper limb rehabilitation [25].

The Nintendo Wii has 3D tracking sensors like an accelerometer, Infrared, and LED sensor bar. However, for this project, an accessory MotionPlus[10] was attached to the remote and add its inertial sensor to increase the overall accuracy. The user's movements in 3D are detected by the remote and then sent via Bluetooth to a PC where the data is filtered and then fed to MATLAB statistics toolbox[11] where the data is processed further and classified.

The evaluation of the device was done by having users perform simple wrist movements by rotating counterclockwise on the x,y, and z-axis and after plotting the 3D trajectory curve of the users and came to a conclusion that classification of the wrist movements can be done with high accuracy. However, more experiments adding more variables proved to be difficult to classify due to the high sensitivity of the remote.

2.2.10. Therapeutic Blobo Bluetooth Ball

Interactive sessions usually help in the consistency of training during rehabilitation. This happens because patients find it more interesting to continue the exercises.

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[10] https://fi.wikipedia.org/wiki/Wii$_{M}otionPlus$

[11] https://se.mathworks.com/products/statistics.html

For that reason, Taiwanese researchers developed a novel [26] and entertaining way for wrist rehabilitation, by using a Blobo Bluetooth ball to perform 4 basic wrist movements (flexion, extension, ulnar deviation, and radial deviation).

The Blobo Bluetooth ball has an accelerometer(to detect the ball's movement), a pressure sensor (to detect when the ball is pressed), and a gyroscope(to measure the ball's rotation). The ball is thrown into the air to connect it to the PC's Bluetooth. A computer game then translates the user's movements transmitted by the ball into the game environment. The game also records the user's activity and saves it to an SQL database.

An experiment was conducted on 10 participants, where 8 of them had wrist impairment. The activities involved playing the computer game where the 4 basic wrist movements are extensively involved. After 8 weeks of experimentation, results showed that the participants with wrist impairment improved about 10° for the ROM in the flexion, extension, and ulnar deviation movements as well as 6° for the radial deviation.

2.2.11. 3D Printed Wrist Rehabilitation System

Creative solutions in rehabilitation are very diverse and come in different forms. A creative design developed for performing wrist exercises aimed at rehabilitation used a computer mouse as inspiration to develop a dome-shaped] [27] object where a patient can exercise 4 wrist movements (flexion, extension, pronation, and supination) by interacting with a computer game.

The physical design of the device consists of a 3D printed object that has an armrest support and a dome-shaped extension that behaves like a computer mouse. The dome-shaped part has an IMU module inside, whose values are used to track the hand movements. The data from the IMU is sent to Arduino where it gets processed to extract the angles and then share the data to a PC via Bluetooth where the data is used in a game environment developed using Unity.

An experiment done using a healthy user required him to move a ball in the game environment to four preset corners. In the assessment of the results, the trajectory of the ball was monitored and conclusions were made. The experiment was found to be successful but more studies are expected to be done, especially using patients to properly ascertain the impact of the design.

2.2.12. IoT Based Patient Monitoring System

An IoT-based solution [28] was suggested, where patient rehabilitation could be first sensed, then acquired for processing, and ultimately be saved on the cloud for further assessment and monitoring.

The wearable sensor consists of an IMU and an optical heart sensor with an ARM Cortex M3 as the processor. The physical design of the wearable sensor is made as an armband. The sensor values are sent to the data acquisition and analysis system via Bluetooth. The latter consists of a Raspberry Pi 3 model that computes the IMU data to represent them in a 3D space. After processing the sensor data, it is then uploaded

Table 2. Summary of rehabilitation techniques and the target areas of the arm

Authors	Actuated design	Virtual Reality and video games	Exoskeleton	Telerehabilitation
Paul [17]	Wrist and Elbow			
Chimsa et al. [18]	Elbow			
de la Iglesia et al. [19]		Arm	Arm	
Lalov and Manolova [20]				Arm and Hand
Phetunuam et al. [21]		Wrist and Forearm		
Sucar et al. [22]		Upper limb		
Zhang et al. [23]				Elbow
Converse et al. [24]		Forearm		
Li et al. [25]		Upper limb		
Hsieh et al. [26]		Wrist		
Ambar et al. [15]		Wrist		
Bilic et al. [16]		Wrist		

to the cloud using WiFi. The data on the cloud is very useful for the follow-up of the patients by the doctors. It allows them to monitor the patient's improvement and efficacy of their rehabilitation routine.

The experimental stage involved a healthy user practicing wrist extension and flexion, with the wrist band on. After, results analysis was in line with the doctor's assumption of a healthy person's ROM.

2.2.13. Summary on the Rehabilitation Study

All the previously reviewed techniques in the study have one thing in common, the need to remove the necessity for the patients to visit a therapist. As interesting as it sounds, there are several approaches made in the study and a brief of the methods used can be seen in Table 2.

When it comes to selecting the best method for rehabilitation, a few criteria were set in terms of interactivity, simplicity and appealingness. This was important because the patients need to do something that they find interesting and hence benefit from it fully. From the reviewed literature virtual reality and video games seemed to catch the attention of the participants. For that reason it was the choice for thee exploration done in this thesis

3. DESIGN AND IMPLEMENTATION

The main purpose of this section is to give a detailed overview of the design and implementation of the system by going in-depth about the components that constitute the system as well as the reasons for these choices.

3.1. Methodology

The goal of our design is for a tennis elbow patient to perform an exercise interactively. It has been studied that squeezing exercises can improve the tennis elbow condition by gradually increasing the grip strength [29]. For this reason, a bottle squeezing exercise was developed where the patient can grab a bottle a certain number of times within a certain period.

To make the experience interactive and immersive, a VR game was developed where the grabbing is translated to a score for encouragement. Moreover, the game setup is made such that there's no therapist required to attend the patient's sessions, therefore making it easy to perform anywhere and anytime.

The implementation of our system requires a hardware controller that can capture the patient's grab pressure and send it to the VR game engine for inclusion. After careful Hardware and software design preferences a set of choices were made and are discussed in the next sections.

3.2. Architecture

The general hardware architecture of the system is shown in figure 1. The development board is the central processing part of the controller and communicates FSR sensor values continuously with the PC to send them to the VR game engine. It uses Bluetooth for this communication. These FSR sensors are distributed on the surface of the bottle for the user's grip to be detected. Additionally, For the user to be able to interact with the environment both the bottle and his arm are attached with Vive trackers for the game to track them. Detailed specifications about these hardware components as well as the Software used to coordinate them are given in the subsequent sections.

3.3. Hardware

3.3.1. Sensors

FSRs were found suitable for this project. The exercise done by grabbing an object could be better interpreted by FSRs. By arranging these FSRs around the object a grab by the subject causes a pressure distribution that alters the resistance of the FSRs and hence a voltage change that can be picked up by a microcontroller. Figure 2 shows the FSR sensor used.

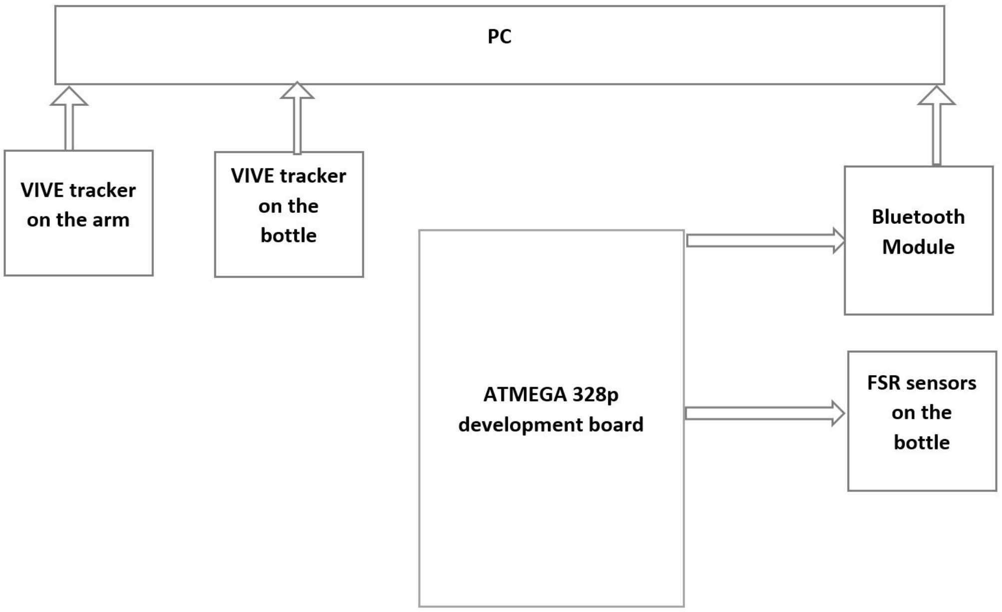

Figure 1. Hardware Architecture

3.3.2. Bluetooth Module

The HC-06 bluetooth shown in figure 3 was chosen for it's simplicity. This class 2 bluetooth [30] doesn't require a separate program for it's function, but can easily work to transmit and receive via serial port interface.

3.3.3. Microcontroller

The processing hardware chosen was the ATMEGA 328p microcontroller. It processes the data from the FSR sensors and sends them to the game engine via Bluetooth. The choice of the ATMEGA 328p was mainly due to its ease of use, especially its support for Arduino IDE that gives access to a wide range of libraries and functions. Additionally, the availability of analog ports makes it suitable for the application as it makes it easy for FSR sensors to get connected to the board. The development board's design and manufacturing become simple. Figure 4 shows the ATMEGA 328p microcontroller.

3.3.4. Development Board

Figure 5 shows a hardware schematic design of the development board of the controller. The design was done using Autodesk Eagle[12]. The design consists of the ATMEGA 328p where there's the interface of FSR, IMU sensors(not used in the

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[12] https://www.autodesk.com/products/eagle/free-download?plc=F360term=1-YEARsupport=ADVANCEDquantity=1

Figure 2. FSR sensor

project), Bluetooth module, and SPI connector. This design was done as a preliminary for a final layout that would be used to produce the final PCB board (Figure 6 shows the final board). The detailed description of the hardware production is documented in Appendix 1.

The ATmega 328p needs 3 minimum connections for its operation. Referring to figure 7 The first is the VCC and Ground power supply with Capacitor C1 acting as a filter for the power rails. Next, is the connection of an oscillator that provides the clock for the microcontroller. In our setup, a 16 MHZ resonator was used. Finally, the last connection is the RESET. It is very useful as it acts as a normal reset to the microcontroller and is also used to signal the bootloader that the microcontroller is in the programming stage(this is explained in Appendix 2). Since the ATmega's Reset is an active low pin, a pull-up resistor R1 is required to maintain it at VCC. Moreover, a push-button S1 is used to activate the RESET by connecting the pin to the ground when pressed.

The Bluetooth interface to the Atmega 328p only requires 4 pins. 2 pins for the power supply and 2 digital pins for the serial port interface. As shown in the figure 8 a potential divider network is used for the Rx pin of the HC06 Bluetooth module

Figure 3. Bluetooth module

because it works on 3.3 volts (say V1) whereas the microcontroller uses 5 volts (say V2). a simple equation below:

$$V1 = V2\frac{R4}{R3 + R4} \tag{1}$$

Substituting the voltage values and assuming R4 to be 2k, results into R3 being approximately 1k. The 4 pins of the Bluetooth are implemented as a 4 pin connector on the PCB board.

The IMU interface is also a 4 pin connection, where 2 pins are used for the power supply and 2 pins (SDA and SCL) for the I2C communication interface.

The SPI interface has a 6 pin connector where 2 pins are for the power supply and the remaining 4 pins are SPI pins(MOSI, MISO, SCK, and RST). The SPI interface is used for two purposes, first to upload the bootloader onto the microcontroller, and second to program the board(more on this can be found in Appendix 1).

The rest of the ports are 2 pin connector for the power supply and a 2 pin connector for the serial port interface.

3.4. Software

This chapter describes the software part of the project. It consists of the microcontroller and VR software. The microcontroller software is responsible for fetching the sensor

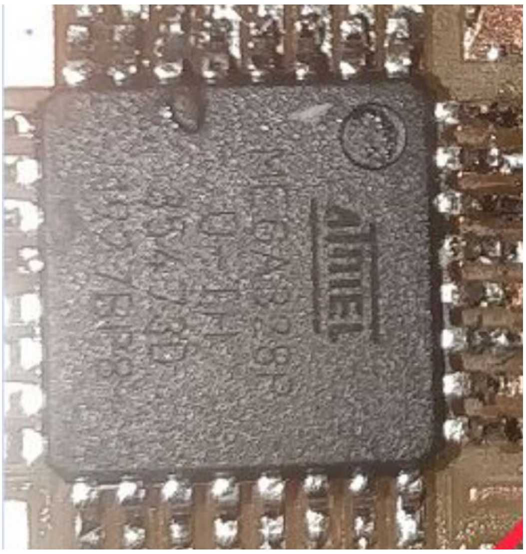

Figure 4. Microcontroller

data and sending it to the Unity input system via Bluetooth. The VR software receives the values and increments a score in the game.

3.4.1. Microcontroller Software

The ATMEGA 328p code was written in C++ and through the Arduino IDE it was uploaded onto the board. The Arduino IDE is a very rich tool that makes it easy for development because of its open source libraries and functions. For that reason the microcontroller software was fast to develop. The main purpose of the code is to read the FSR sensor data and send it to the Bluetooth module via serial port.

As shown in the flow chart of figure 9 The Code instructs the microcontroller to read the FSR sensor data from the analog port, and since the ATMEGA 328p has a 10 bit ADC it is first converted to an 8 bit scale for a better interpretation. After this, the sensor values are sent to the serial port where the Bluetooth module is connected. From this stage the VR software takes care of the rest.

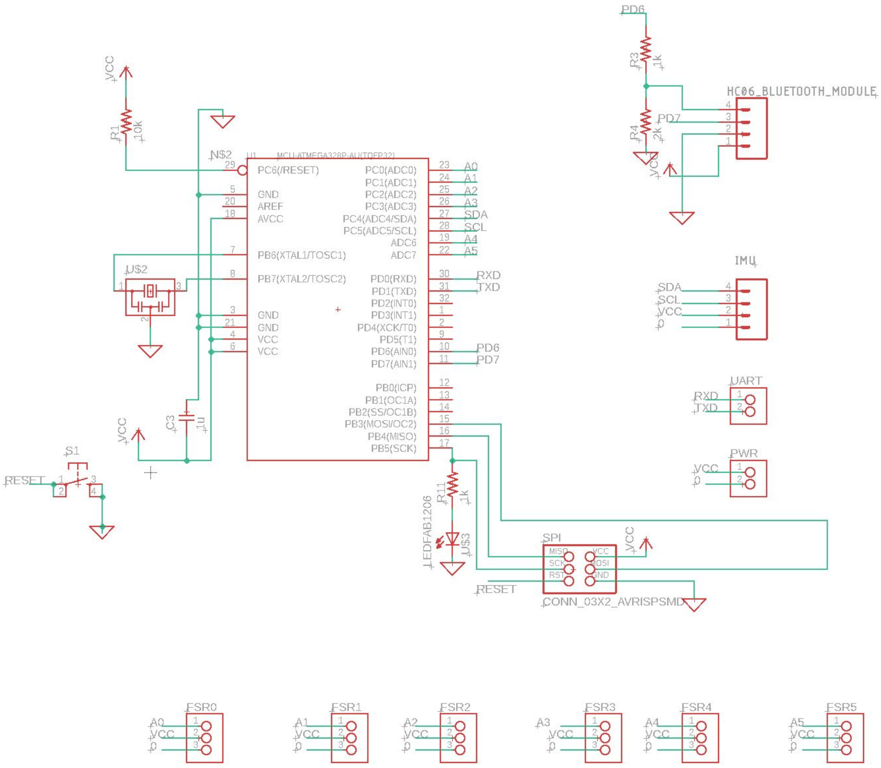

Figure 5. Hardware Schematic

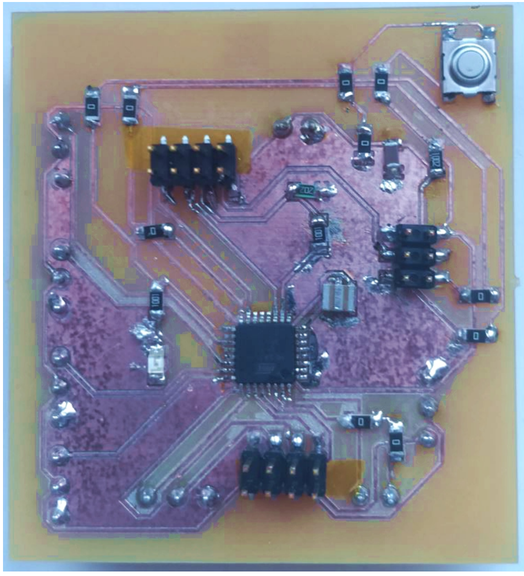

Figure 6. Development board after manufacturing

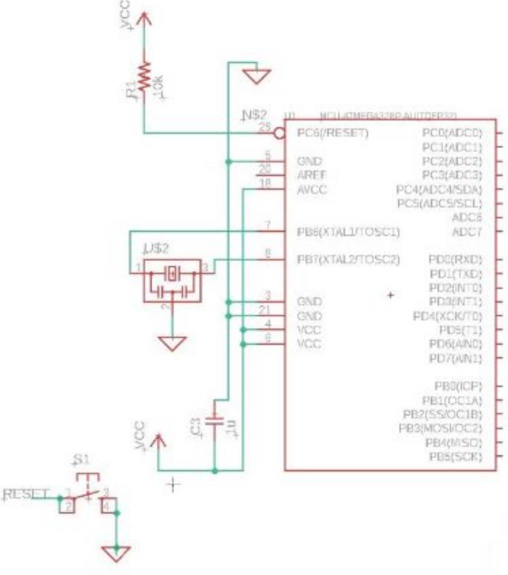

Figure 7. ATMEGA 328p connections

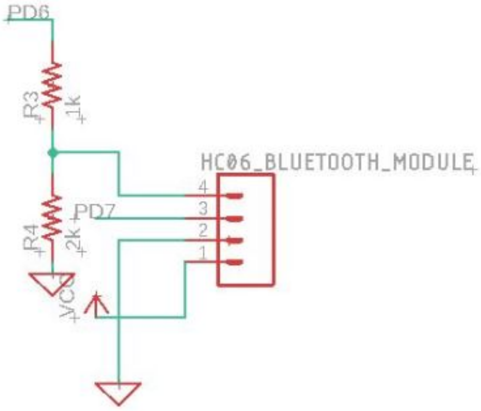

Figure 8. Bluetooth interface

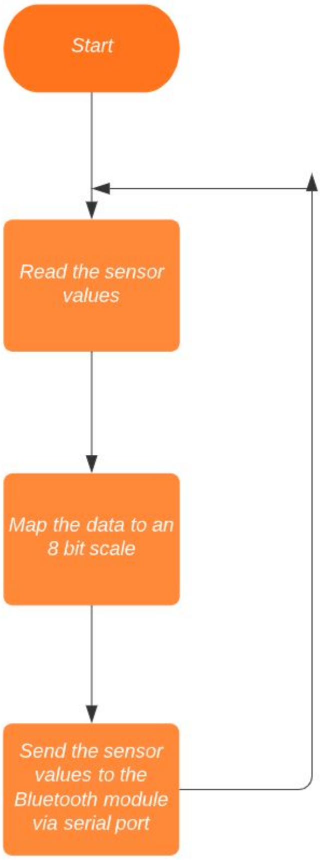

Figure 9. Microcontroller Software flow chart

4. EVALUATION

This chapter discusses the experimental setup for the evaluation of the designed system. After describing the experimental setup, details about the participants are provided. Further, there is a detailed account of the experiment procedure and lastly, about data collected for the analysis.

4.1. Experimental Setup

The experimental setup included Lenovo Thinkpad T15G PC with NVIDIA RTX 2080 graphics card, an HTC VIVE Pro 2 headset with two base stations. The custom-designed VR controller encased in the test object (a bottle), and two VIVE Trackers were used, one fitted on the arm of the participant and the other put on the bottle.

The experimental device, as shown in Figure 10 consists of a bottle that has the custom VR controller fixed at the bottom and with 3 FSR sensors fixed on its surface for an easy grip by the participants. Additionally, a VR tracker is fixed on the top to track the object in the environment.

Figure 10. Experimental device consisting of prototype with FSR sensors, board and HTC VIVE Tracker (left down); strap with HTC VIVE Tracker (right); and HTC VIVE Pro 2 headset (top).

The Virtual environment is based on the free unity asset, coffee shop starter pack[13]. In this scene, the user appears to be in a coffee shop and sitting on the table. The Tracker fitted on his arm is rendered as arm in the VR scene, and the bottle is modelled as a glass by using the Tracker on the bottle. Figure 11 shows the scene's look.

The experiment was set up such that the FSR sensor values are continuously sent to the VR environment, and from there, C# scripts compare it with a threshold value above which a grab is detected. The threshold was found after carefully studying the

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[13] https://assetstore.unity.com/packages/3d/props/coffeeshop-starter-pack-160914

FSR values that respond the best to a grab. After a successful grab is detected, a score that is included in the scene as shown in Figure 16 is incremented and, as will be shown later, would become essential for the analysis.

Figure 11. VR scene (coffee shop environment with table and object to grab).

Figure 12. Score displayed above the scene.

4.2. Participants

For the experiment, 8 participants (of which one was woman) were recruited; their age ranged from 21 to 33 years old. In addition, all the participants were healthy users and right-handed. All the participants except one, were students at the University of Oulu. Only 3 of the participants reported having a prior experience with VR.

4.3. Experimental Procedure

4.3.1. Procedure Before Experiment

Every participant was briefed about the safety measures taken to conduct the experiment; for example, they were provided with hand sanitiser, face mask and asked to keep a safe distance. Besides the face mask, the researcher had to wear gloves every time while dealing with the participants. Between each participant, the research space was well ventilated, surfaces cleaned, and VR headset and other hardware were disinfected using UV light equipment as shown in figure 13.

Next, the participants were briefed about the experiment and its objectives and asked to read and sign an Informed consent and meet requirements for participation (not being pregnant or have epilepsy). Every recruit was given a participant ID according to the order they came in. This ID was later used to identify the participant individually throughout the experiment.

After the explanation and consent, the participants were given a questionnaire, where demographic questions, as well as their prior experience with VR, were asked. Afterwards, they were asked to put on the VR headset, then fitted with one Tracker on the arm by means of a strap and asked to perform two exercises.

Figure 13. UV light desinfection

4.3.2. Procedure during Experiment

The first exercise asked the participant to grab and mildly squeeze the bottle 15 times in a span of 45 seconds, and the second exercise was repetition but for 10 times within

30 seconds. The score increases as the repetitions of grab and release are carried out. Figure 14 shows one of the participants performing the exercises.

Figure 14. participant performing the exercises

4.3.3. *Procedure after Experiment*

After the experiment, each participant's score was entered, and they were asked to answer a post-experiment questionnaire based on the NASA Task Load Index (TLX)[14].

4.4. Data Collection

4.4.1. *VR Performance Data*

Table 3 shows the participants scores after performing the exercises. It also shows the average and standard deviation for each exercise. It was observed that for the first exercise most of the participants were trying to get used to the environment, but in the second exercise it became easier to carry out.

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[14] https://humansystems.arc.nasa.gov/groups/tlx/

Table 3. Participant scores

Participant ID	**1st session score**	**2nd session score**
1	8	31
2	42	31
3	42	26
4	8	19
5	47	20
6	14	10
7	21	20
8	31	17
Average	26.625	21.75
Standard deviation	14.966	6.741

4.4.2. Task Load Index (TLX) Data

The NASA TLX questionnaire was used for collecting data about the participants' experience. As shown in figure 15 It measures the workload of this experiment by assessing from scale of 1 (very low) to 5 (very high), 6 important measures, which are: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration.

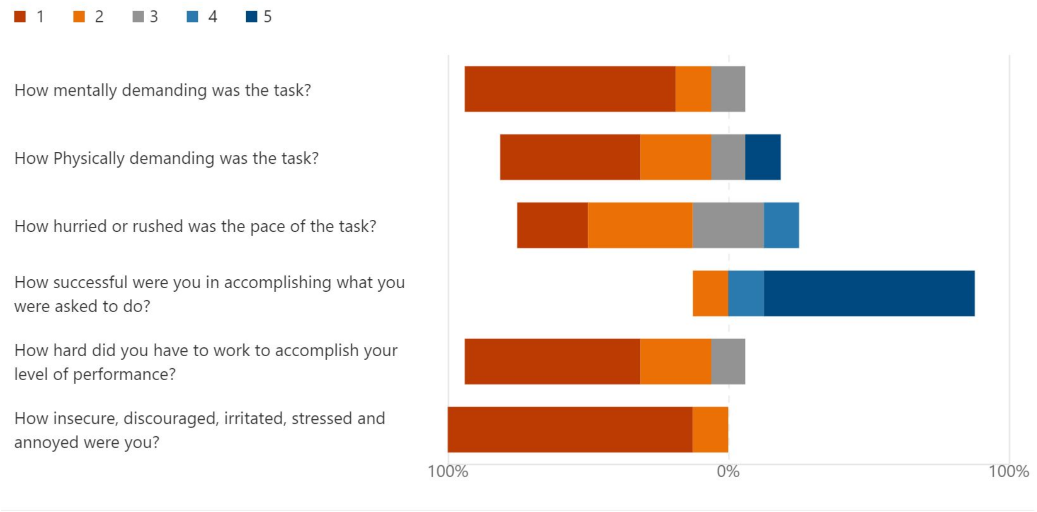

Figure 15. Task load index data results (1 - Very low; 5 - Very high)

4.5. Discussion

4.5.1. User Experience

According to the task load index data collected from the users, we see that mental demand for the task was very low for a large majority; this gives positive feedback about the possibility that real users could adapt to it easily. Secondly, for the physical demand, the majority saw it as very low, but one person reported it as very highly demanding. Therefore, a thorough analysis would require approaching that person for further clarification. Next, about the pace of the experiment, the feedback is mixed, but on average, the pace could be termed as not too rushed. This again would be positive feedback because rehabilitation should be performed at a suitable pace for the patient. Most of the participants also reported a very high success rate in completing the exercises; in many cases, many of them finished before the required time. Finally, all the participants reported a very low Effort and frustration in completing the exercises.

The scores of Table 3 show us the need for repetition during rehabilitation exercises; it not only helps with a possibility of fast recovery but also makes the exercises easy to master. As seen from the scores, some participants did not score better in the first exercise, but the scores variations improved in the second one, as showcased by the decreased standard deviation.

4.5.2. Limitations

Although the FSR sensors used are one of the most researched, cheap and stable FMG sensors. They are prone to hysteris [31] because of their voltage dependence. Therefore readings vary from one experiment to the other. Piezocapacitive FMG sensors could work as a better alternative, but the cost may increase.

Another limitation worthy of attention could be the VR environment. The current environment could be made more interactive and more game-like for the patients to be motivated to practice more. However, the implemented score setting is a very promising good start at making it attractive because patients still get motivated to achieve a higher score.

4.5.3. Future Implementation

As far as tennis elbow is involved, a variety of exercises can help with fast recovery. There is a need to incorporate elbow exercises, like elbow flexion and extension as well as more wrist exercises that also exercise more muscles. With this could come a new challenge to build a more suitable controller and also implement complex algorithms in order to differentiate between different kinds of movements and gestures. Also, sensors would need to be more accurate and possibly use a combination of various sensors to achieve better results and performance.

Another interesting improvement would be to ask questions to the users about their feeling of presence within the environment. As clearly stated by Barhoush et al. [32] there is a need to collect data about the sense of the presence of the participants. If successful, it would make more sense in terms of rehabilitation because it would encourage the users to stay in the game more as it becomes close to reality for them.

5. CONCLUSION

The work done in this study was to design and implement a VR controller device for sports-related injuries and, in particular, for people with tennis elbow. This injury is introduced at the beginning of the study, where its prevalence, symptoms, and treatment are discussed. Then, emphasis was then put on using VR for rehabilitation and its benefits. Later in the discussion, the desired rehabilitation exercise was explored as well as the hardware and its computational requirements. Sensors were an important consideration because of the need to model the therapy exercise in VR accurately. Although the focus was on the wrist, there was interest in the elbow sensing for future implementation and study.

After this, a detailed review was done on the wrist and elbow sensing, where numerous sensors were reviewed based on the operating principle, performance, and sometimes cost. At the end of this review, the FSR sensors were deemed promising because they were found to be easy to use, cheap and accurate. However, knowledge of sensors alone was not enough to work with; therefore, a second review that focused on using different techniques that use these sensors for rehabilitation purposes was studied. This review explored a lot of different approaches to designing therapy-focused controllers. This review helped to understand better the usefulness of using games in therapy and hence VR, which was the subject of this thesis.

The hardware design and manufacturing were clearly described. The design with software tool Eagle is described in detail in chapter 3, as well as design considerations and interfaces. The hardware manufacturing and testing were also clearly documented in a step-by-step fashion and can be found in Appendices 1 and 2. Here, the digital fabrication method of PCB design is explored and the different hardware testing methods. The resulting hardware controller proved to be robust and was used without issues throughout the whole implementation.

A VR environment design was done in collaboration with colleagues. It was made for the particular test exercise that was studied. Finally, a final experiment was carried out to ascertain the impact of the exercise on healthy users. Data collection was the rating factor for the overall experience.

The results from the data collected from the participants showed positive feedback about the experiment. Upon reflection on the results and the approach used, there is a need to make future improvements to the methodology. For example, there is a need to incorporate more exercises using different parts, such as the elbow. On the bright side, the initial review about the wrist and elbow gives a sense of what could be done, and suitable sensors and hardware controllers can be deduced and implemented.

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7. APPENDICES

Appendix 1 Hardware Manufacturing

The hardware design shown in figure 16 represents the schematic (figure 16a) and layout (figure 16b) of the controller. The PCB design was done in Autodesk Eagle. The schematic looks different from the original one presented in chapter 3 because this one was modified to include bypass resistors for ease of routing in a single layer design.

In this chapter detailed explanation of the PCB manufacturing process will be done starting from the generation of PCB files to the final soldered board. The LPKF[15] milling machine was used to produce the board. First, LPKF milling files are generated using Autodesk Eagle and then these files are used by the LPKF software to give milling instructions to the milling machine. After the board is produced, components are soldered to it and eventually tested to confirm that it works properly.

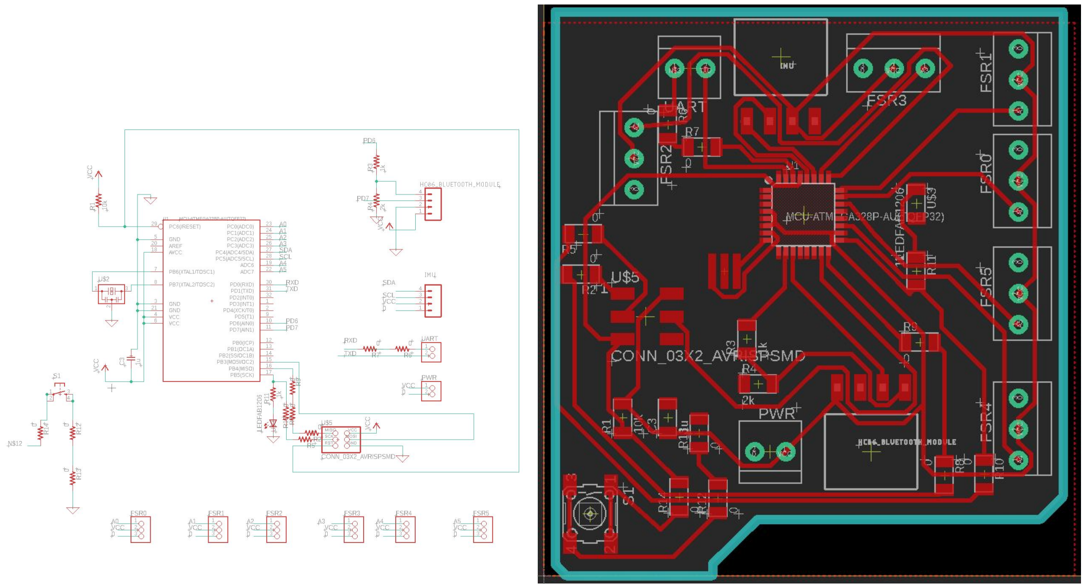


Figure 16. Hardware Schematic (Left) and Layout (Right)

7.1. Generating Gerber and Exellion Drill Files

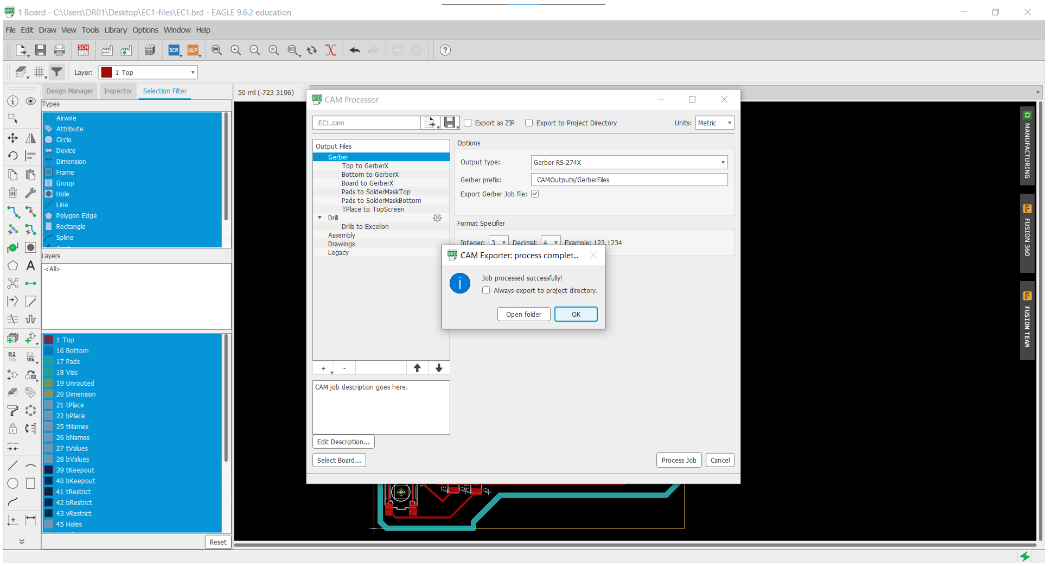
The Gerber and Exellion drill files are used to share PCB layout information (like top layer structure, outline and drills) to the milling machine in order to correctly produce the board. The steps followed to generate these files are as follows:

---

[15] https://hci.rwth-aachen.de/mill

1. Download the LPKF CAM file from here[16].

2. From Eagle Layout window go to **FIle> CAM Processor** from here select **Load job file** and upload the CAM file downloaded from step 1. After this press on **Process Job** as shown in figure 17.



EC1.cam ☐ Export as ZIP ☐ Export to Project Directory Units: Metric

Output type: Gerber RS-274X

Gerber prefix: CAMOutputs/GerberFiles

Export Gerber Job file: ☑

Format Specifier: Integer: 3 Decimal: 4 Example: 123.1234

CAM job description goes here.

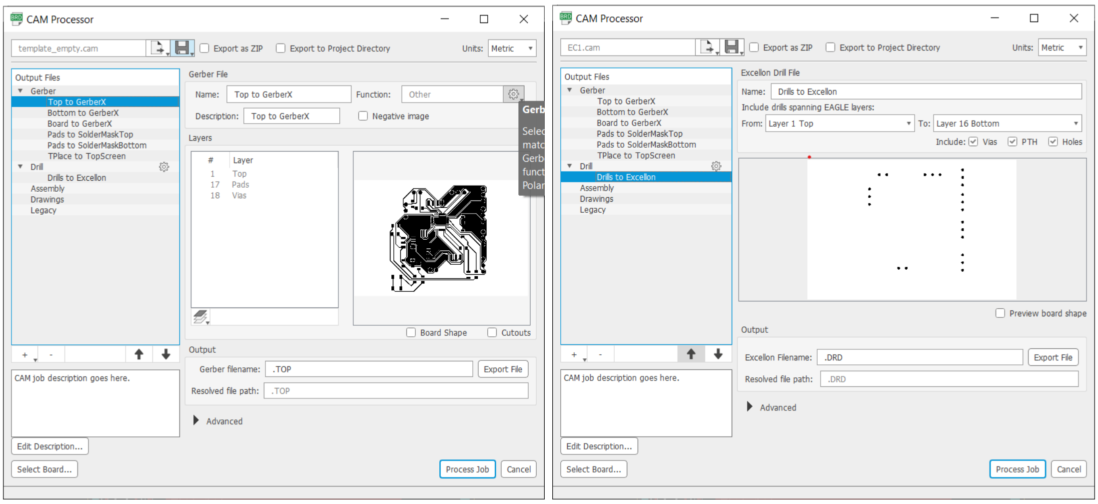
CAM Exporter: process complet...

Job processed successfully!

☐ Always export to project directory.

Figure 17. Generating Gerber and Exellion drill files.

3. After the files are generated, the CAM processor window shows the preview of the top layer and drill files generated (more files are generated but for our application, these two were the necessary). They're shown in figure18. The top layer consists of routing wires and pads whereas drilling files are drills put in the design for various purposes.



template_empty.cam ☐ Export as ZIP ☐ Export to Project Directory Units: Metric

Gerber File — Name: Top to GerberX Function: Other

Description: Top to GerberX ☐ Negative image

#	Layer
1	Top
17	Pads
18	Vias

Gerber filename: .TOP

Resolved file path: .TOP

CAM job description goes here.

EC1.cam ☐ Export as ZIP ☐ Export to Project Directory Units: Metric

Excellon Drill File — Name: Drills to Excellon

Include drills spanning EAGLE layers:

From: Layer 1 Top To: Layer 16 Bottom

Include: ☑ Vias ☑ PTH ☑ Holes

Excellon Filename: .DRD

Resolved file path: .DRD

CAM job description goes here.

Figure 18. Top (Left) and Drill (Right) files

---

[16] https://hci.rwth-aachen.de/mill

7.2. Milling

After generating the LPKF files the next step is to use the milling machine to produce the board. The LPKF machine shown in figure 19 (a) can produce single and multi-layer PCBs and it has an automatic[17] tool switching while producing the board. The layout from Autodesk eagle is extracted through Gerber and Exellion drill files and then fed to the LPKF for manufacturing. The process follows the steps desribed below:

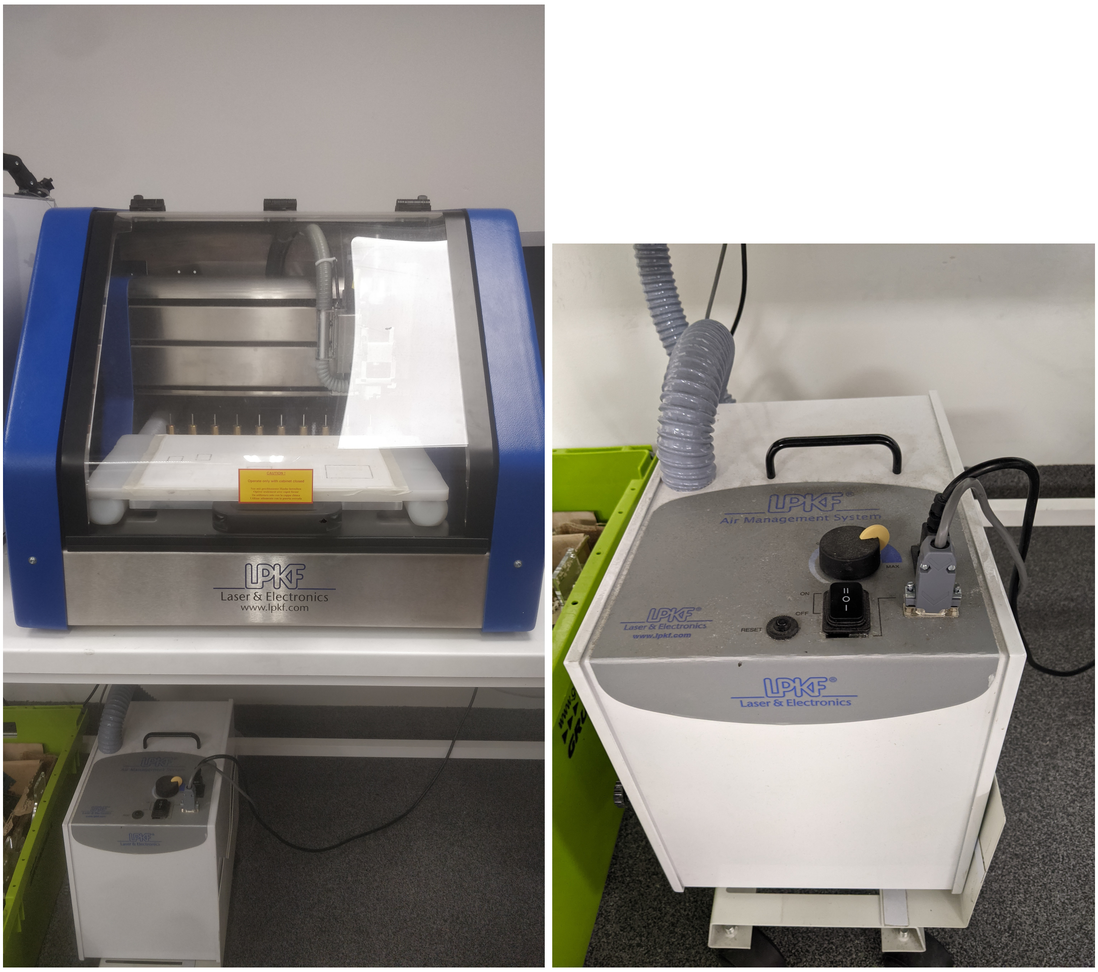


Figure 19. a) LPKF milling machine b) Power supply

1. Switch on the LPKF machine using its power supply shown in figure 19 (b)
2. Place and tape the contour of an FR4 copper board on to the vacuum table of the milling machine. This vacuum table helps to align the board by using air suction. Figure 20 shows the setup.
3. After the board is correctly placed open **LPKF Circuit Pro** software and go to **File>Import** and select the Gerber and Exellion drill files (.BOA, .DRD and .TOP) as shown in figure 21 After these files are uploaded the board layout is previewed in the window.
4. Next, go to **Process Planning Wizard** select the **type of the process** as **Process PCBs** and **Number of Layers** as **Single-sided top** to chose a single layer process. Finally choose the **Subsrate type** as **FR4** copper.

---

[17] https://hci.rwth-aachen.de/mill

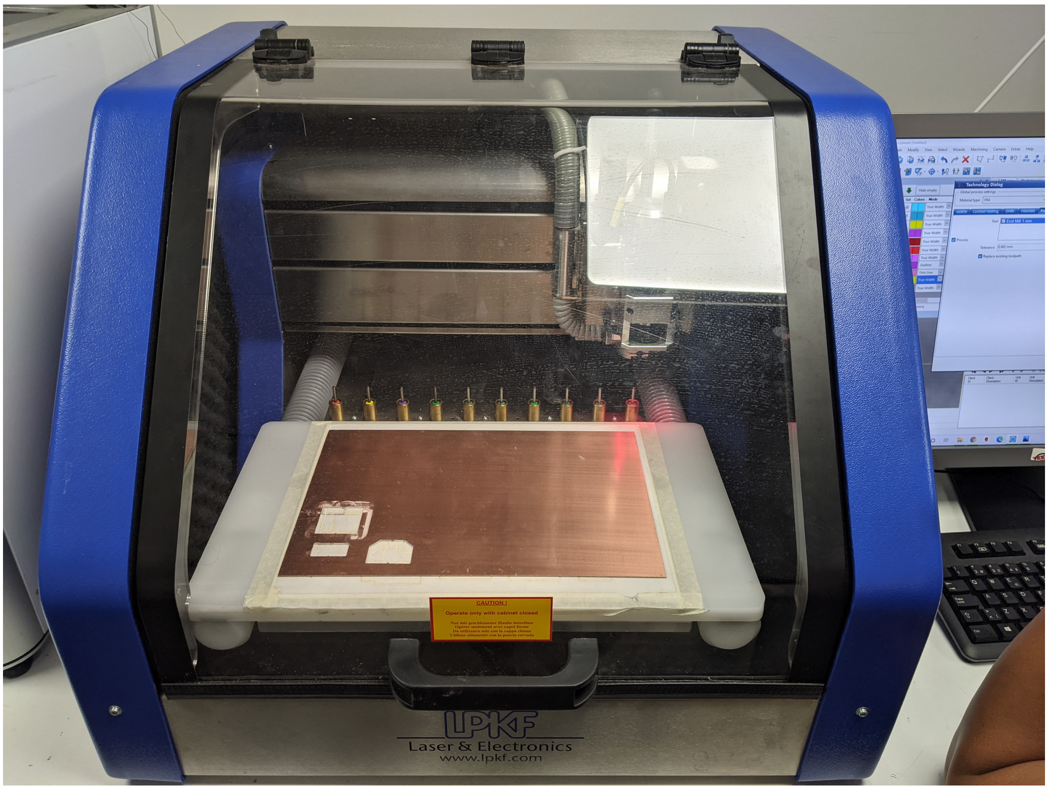
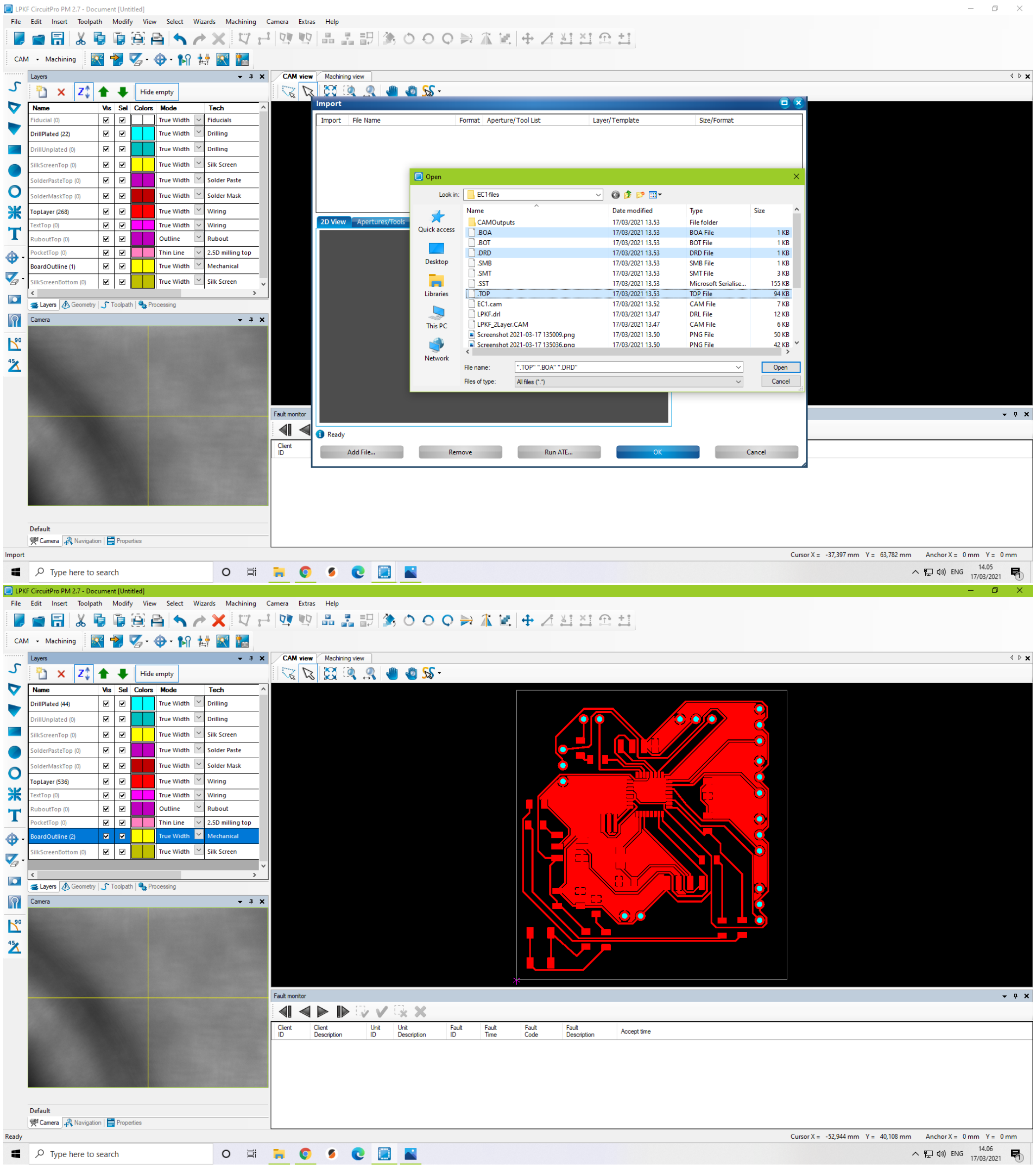


Figure 20. Board alignment

5. Open **Technology dialog** and under **Isolate** select the style shown in figure 24 and same for **Contour routing**. Also, Change the **Copper layer thickness** to the available board which is 35 um. The rest can remain default. These settings define the isolation width between wires, tools to be used, and contour styles of some of the pads. After these settings are analyzed the software computes the milling tool paths as shown in figure 25 (a), it also reviews the milling tools availability and condition. At this stage, the software has identified the Layout structure and the tool path to follow while milling the board. Additionally, it has an idea of the board type and thickness, therefore the remaining steps are to start the actual milling steps.
6. In this step open **Board production wizard** then click next up to **Material settings**(if the board is already placed in the machine) Under **Material settings** (shown in figure 26 (a)) it shows the board dimensions and enter the Board's width and length for the machine to know how large is the board it will be operating with. Click continue, to go to **Placement** where the actual PCB to be manufactured is placed inside the area of the whole board which was previously defined.
7. After clicking continue, to **Marking drills**, the milling machine will start marking the drills of the holes present in the layout. After this is done, the software will need calibration to perform the rest of the work, this is done by choosing a place outside the main layout where a line can be milled. The milling machine's internal camera will then take a picture of the line and the user measures the thickness of it as shown in figure 27 (b).
8. The Machine starts to mill the board and the milling progress is shown in figure 28. The Milled part is shown by the yellow traces.



a)

Name	Vis	Sel	Colors	Mode	Tech
Fiducial (0)	☑	☑	⬜	True Width	Fiducials
DrillPlated (22)	☑	☑	🟦	True Width	Drilling
DrillUnplated (0)	☑	☑	🟦	True Width	Drilling
SilkScreenTop (0)	☑	☑	🟨	True Width	Silk Screen
SolderPasteTop (0)	☑	☑	🟪	True Width	Solder Paste
SolderMaskTop (0)	☑	☑	🟥	True Width	Solder Mask
TopLayer (268)	☑	☑	🟥	True Width	Wiring
TextTop (0)	☑	☑	🟪	True Width	Wiring
RuboutTop (0)	☑	☑	🟪	Outline	Rubout
PocketTop (0)	☑	☑	🟪	Thin Line	2.5D milling top
BoardOutline (1)	☑	☑	🟨	True Width	Mechanical
SilkScreenBottom (0)	☑	☑	🟨	True Width	Silk Screen

Look in: EC1-files

Name	Date modified	Type	Size
CAMOutputs	17/03/2021 13.53	File folder	
.BOA	17/03/2021 13.53	BOA File	1 KB
.BOT	17/03/2021 13.53	BOT File	1 KB
.DRD	17/03/2021 13.53	DRD File	1 KB
.SMB	17/03/2021 13.53	SMB File	1 KB
.SMT	17/03/2021 13.53	SMT File	3 KB
.SST	17/03/2021 13.53	Microsoft Serialise...	155 KB
.TOP	17/03/2021 13.53	TOP File	94 KB
EC1.cam	17/03/2021 13.52	CAM File	7 KB
LPKF.drl	17/03/2021 13.47	DRL File	12 KB
LPKF_2Layer.CAM	17/03/2021 13.47	CAM File	6 KB
Screenshot 2021-03-17 135009.png	17/03/2021 13.50	PNG File	50 KB
Screenshot 2021-03-17 135036.png	17/03/2021 13.50	PNG File	42 KB

File name: ".TOP" ".BOA" ".DRD"
Files of type: All files (*.*)

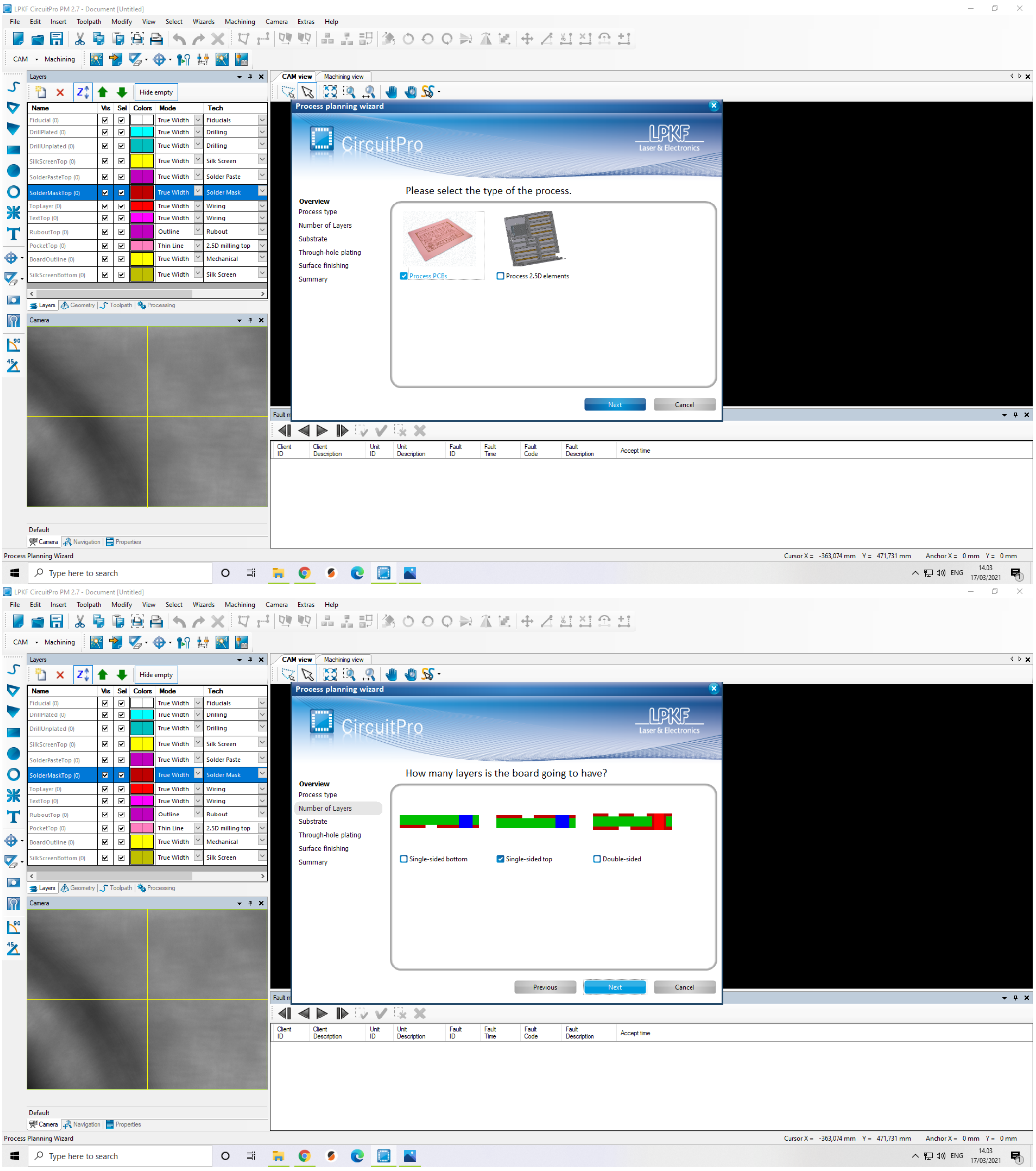
b)

Name	Vis	Sel	Colors	Mode	Tech
DrillPlated (44)	☑	☑	🟦	True Width	Drilling
DrillUnplated (0)	☑	☑	🟦	True Width	Drilling
SilkScreenTop (0)	☑	☑	🟨	True Width	Silk Screen
SolderPasteTop (0)	☑	☑	🟪	True Width	Solder Paste
SolderMaskTop (0)	☑	☑	🟥	True Width	Solder Mask
TopLayer (536)	☑	☑	🟥	True Width	Wiring
TextTop (0)	☑	☑	🟪	True Width	Wiring
RuboutTop (0)	☑	☑	🟪	Outline	Rubout
PocketTop (0)	☑	☑	🟪	Thin Line	2.5D milling top
BoardOutline (2)	☑	☑	🟨	True Width	Mechanical
SilkScreenBottom (0)	☑	☑	🟨	True Width	Silk Screen

Figure 21. a) Uploading files b) Board Layout

9. After the milling completes the tool shows **Board production Finished** as shown in figure 29.

Finally, the Board was milled and the last step of manufacturing was soldering the components on the PCB. The final result is shown in figure 30.



Name	Vis	Sel	Colors	Mode	Tech
Fiducial (0)	☑	☑	⬜	True Width	Fiducials
DrillPlated (0)	☑	☑	🟦	True Width	Drilling
DrillUnplated (0)	☑	☑	🟦	True Width	Drilling
SilkScreenTop (0)	☑	☑	🟨	True Width	Silk Screen
SolderPasteTop (0)	☑	☑	🟪	True Width	Solder Paste
SolderMaskTop (0)	☑	☑	🟥	True Width	Solder Mask
TopLayer (0)	☑	☑	🟥	True Width	Wiring
TextTop (0)	☑	☑	🟪	True Width	Wiring
RuboutTop (0)	☑	☑	🟪	Outline	Rubout
PocketTop (0)	☑	☑	🟪	Thin Line	2.5D milling top
BoardOutline (0)	☑	☑	🟨	True Width	Mechanical
SilkScreenBottom (0)	☑	☑	🟨	True Width	Silk Screen

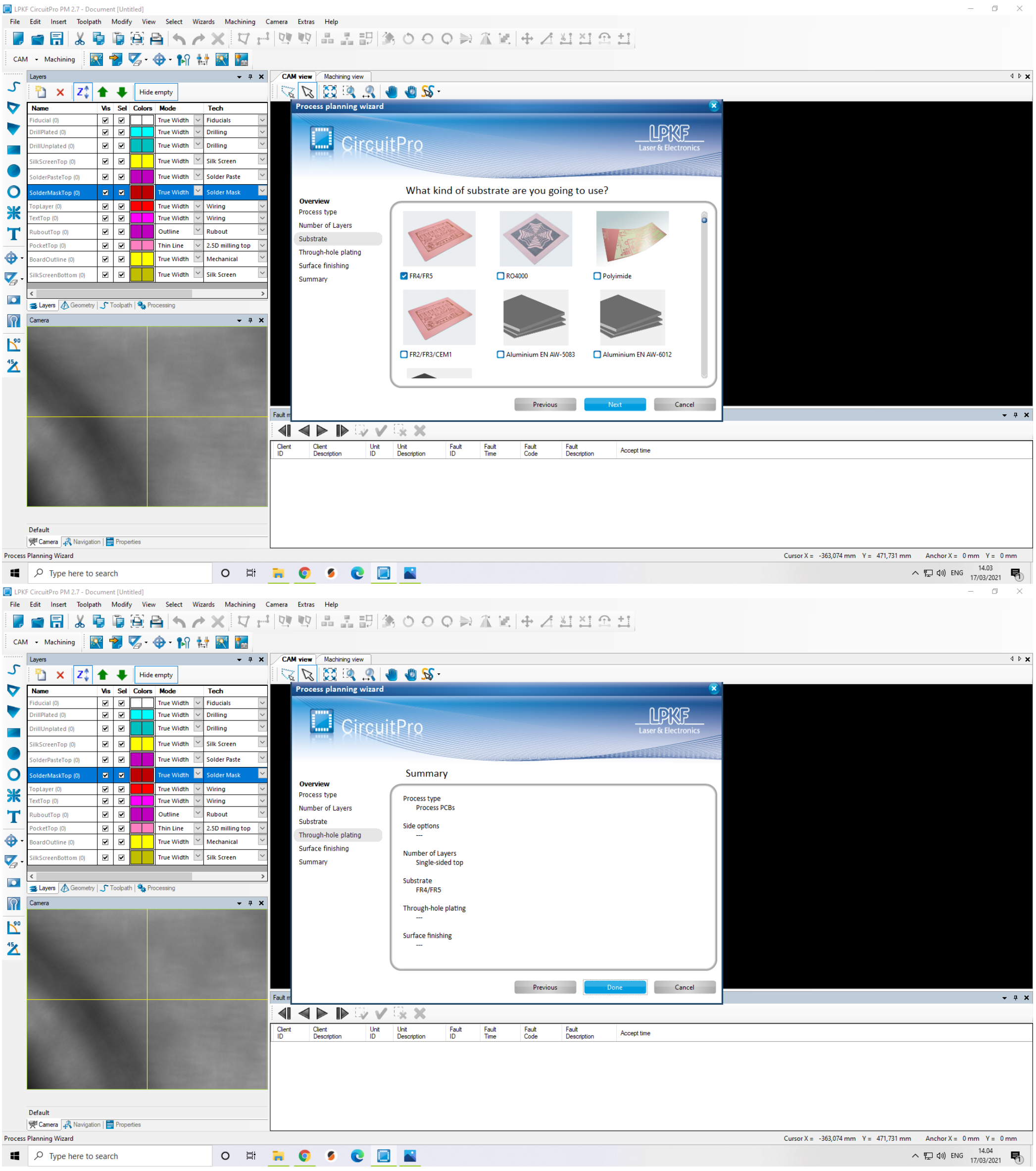
Please select the type of the process.

☑ Process PCBs ☐ Process 2.5D elements

How many layers is the board going to have?

☐ Single-sided bottom ☑ Single-sided top ☐ Double-sided

Figure 22. a) Type of Process b) Number of layers



What kind of substrate are you going to use?

☑ FR4/FR5
☐ RO4000
☐ Polyimide
☐ FR2/FR3/CEM1
☐ Aluminium EN AW-5083
☐ Aluminium EN AW-6012

Summary

Process type
Process PCBs

Side options

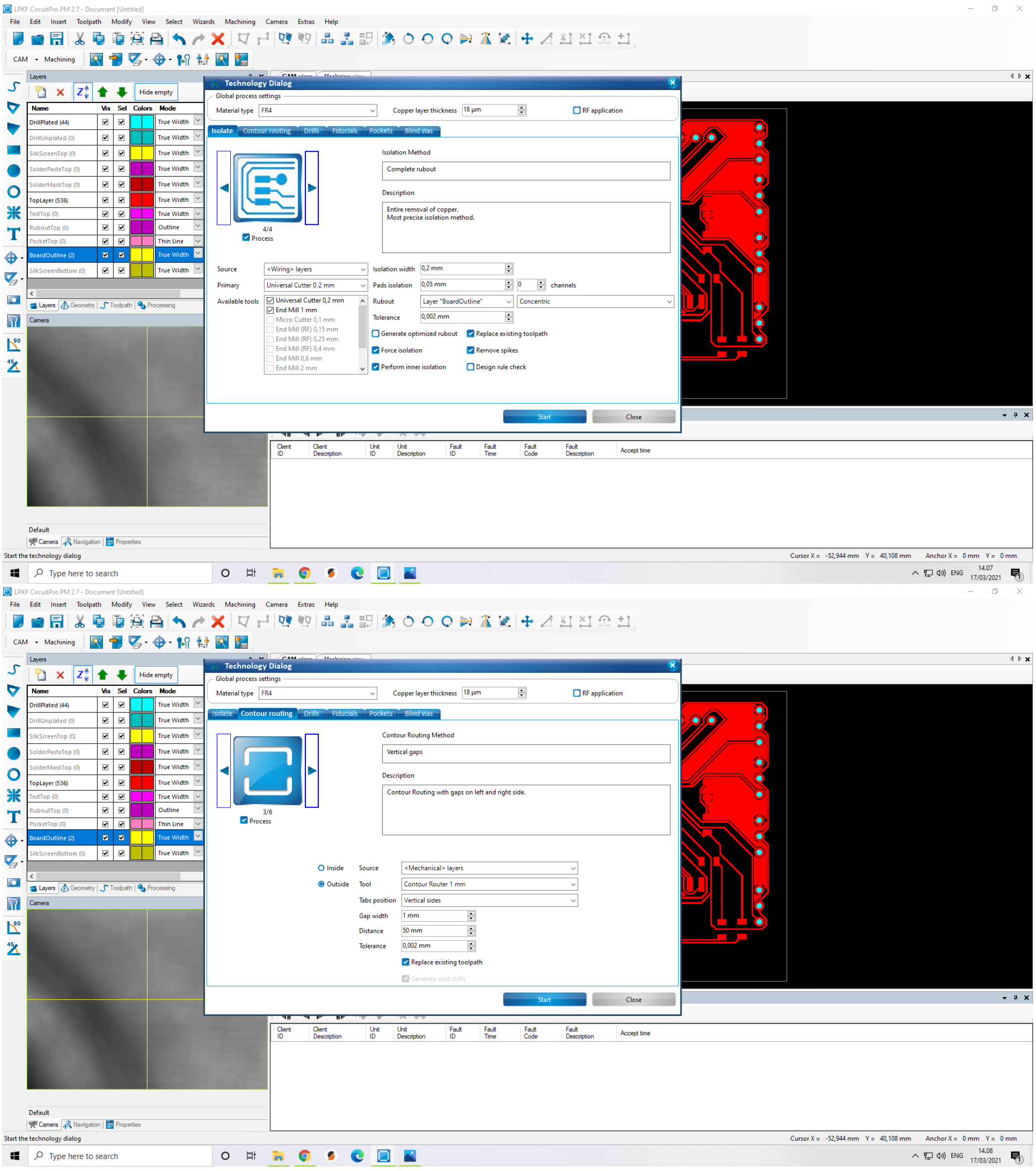
Number of Layers
Single-sided top

Substrate
FR4/FR5

Through-hole plating

Surface finishing

Figure 23. a) Type of material b) Summary of Process selection



Technology Dialog

Global process settings

Material type: FR4

Copper layer thickness: 18 µm

☐ RF application

Isolate

Isolation Method: Complete rubout

Description: Entire removal of copper.
Most precise isolation method.

4/4

☑ Process

Source: <Wiring> layers

Primary: Universal Cutter 0,2 mm

Available tools:
- ☑ Universal Cutter 0,2 mm
- ☑ End Mill 1 mm
- ☐ Micro Cutter 0,1 mm
- ☐ End Mill (RF) 0,15 mm
- ☐ End Mill (RF) 0,25 mm
- ☐ End Mill (RF) 0,4 mm
- ☐ End Mill 0,8 mm
- ☐ End Mill 2 mm

Isolation width: 0,2 mm

Pads isolation: 0,05 mm, 0 channels

Rubout: Layer "BoardOutline", Concentric

Tolerance: 0,002 mm

☐ Generate optimized rubout
☑ Replace existing toolpath
☑ Force isolation
☑ Remove spikes
☑ Perform inner isolation
☐ Design rule check

Technology Dialog

Global process settings

Material type: FR4

Copper layer thickness: 18 µm

☐ RF application

Contour routing

Contour Routing Method: Vertical gaps

Description: Contour Routing with gaps on left and right side.

3/6

☑ Process

○ Inside
● Outside

Source: <Mechanical> layers

Tool: Contour Router 1 mm

Tabs position: Vertical sides

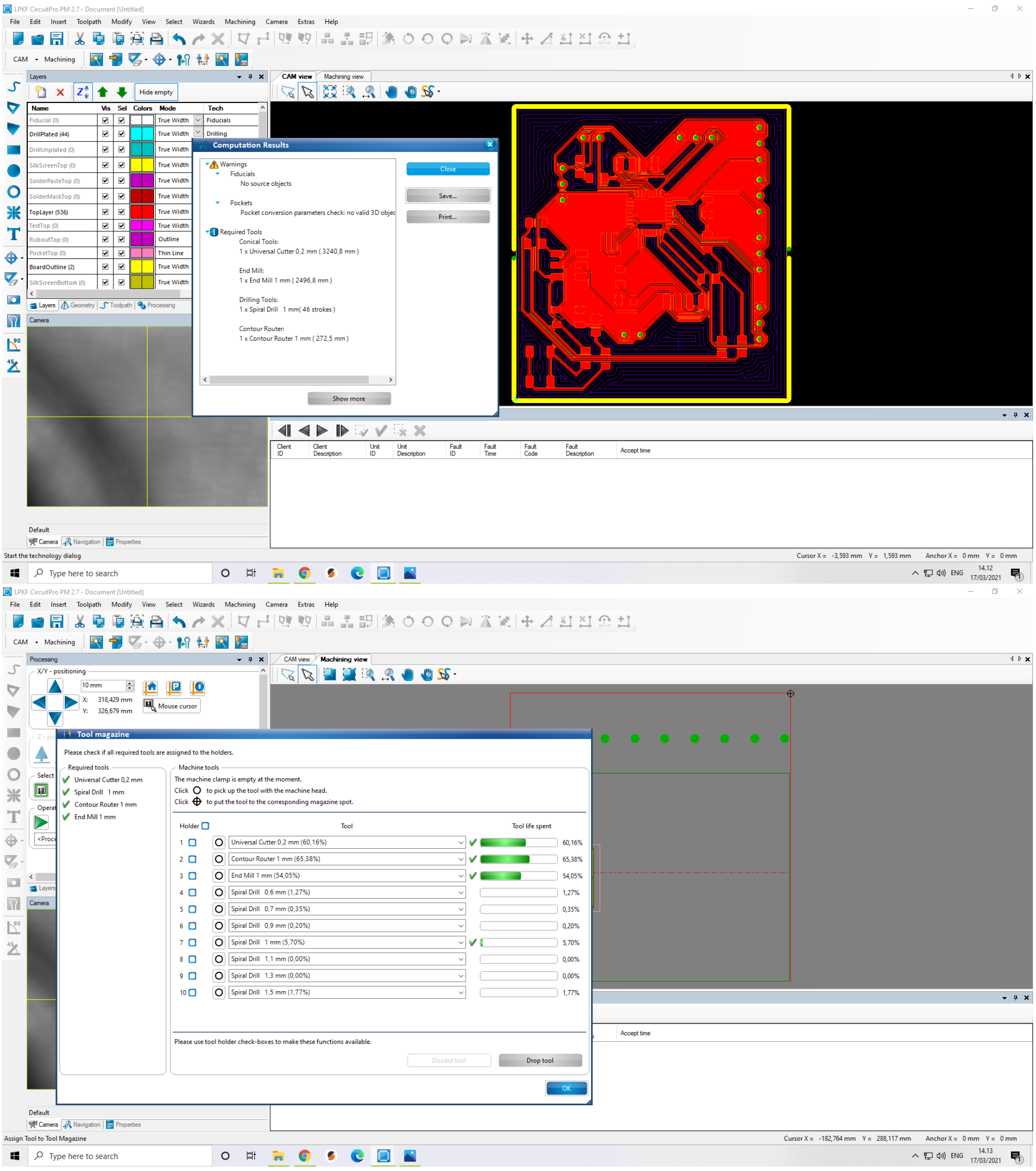
Gap width: 1 mm

Distance: 50 mm

Tolerance: 0,002 mm

☑ Replace existing toolpath
☑ Generate start drills

Figure 24. a) Isolate settings b) Contour Routing



Name	Vis	Sel	Colors	Mode	Tech
Fiducial (0)	☑	☑	⬜	True Width	Fiducials
DrillPlated (44)	☑	☑	🟦	True Width	Drilling
DrillUnplated (0)	☑	☑	🟦	True Width	
SilkScreenTop (0)	☑	☑	🟨	True Width	
SolderPasteTop (0)	☑	☑	🟪	True Width	
SolderMaskTop (0)	☑	☑	🟥	True Width	
TopLayer (536)	☑	☑	🟥	True Width	
TextTop (0)	☑	☑	🟪	True Width	
RuboutTop (0)	☑	☑	🟪	Outline	
PocketTop (0)	☑	☑	🟪	Thin Line	
BoardOutline (2)	☑	☑	🟨	True Width	
SilkScreenBottom (0)	☑	☑	🟨	True Width	

Computation Results

- Warnings
  - Fiducials
    - No source objects
  - Pockets
    - Pocket conversion parameters check: no valid 3D objec
- Required Tools
  - Conical Tools:
    1 x Universal Cutter 0,2 mm (3240,8 mm)
  - End Mill:
    1 x End Mill 1 mm (2496,8 mm)
  - Drilling Tools:
    1 x Spiral Drill 1 mm(46 strokes)
  - Contour Router:
    1 x Contour Router 1 mm (272,5 mm)

Start the technology dialog

Cursor X = -3,593 mm Y = 1,593 mm Anchor X = 0 mm Y = 0 mm

10 mm
X: 318,429 mm
Y: 326,679 mm

Tool magazine

Please check if all required tools are assigned to the holders.

Required tools
- ✓ Universal Cutter 0,2 mm
- ✓ Spiral Drill 1 mm
- ✓ Contour Router 1 mm
- ✓ End Mill 1 mm

Machine tools

The machine clamp is empty at the moment.
Click ○ to pick up the tool with the machine head.
Click ⊕ to put the tool to the corresponding magazine spot.

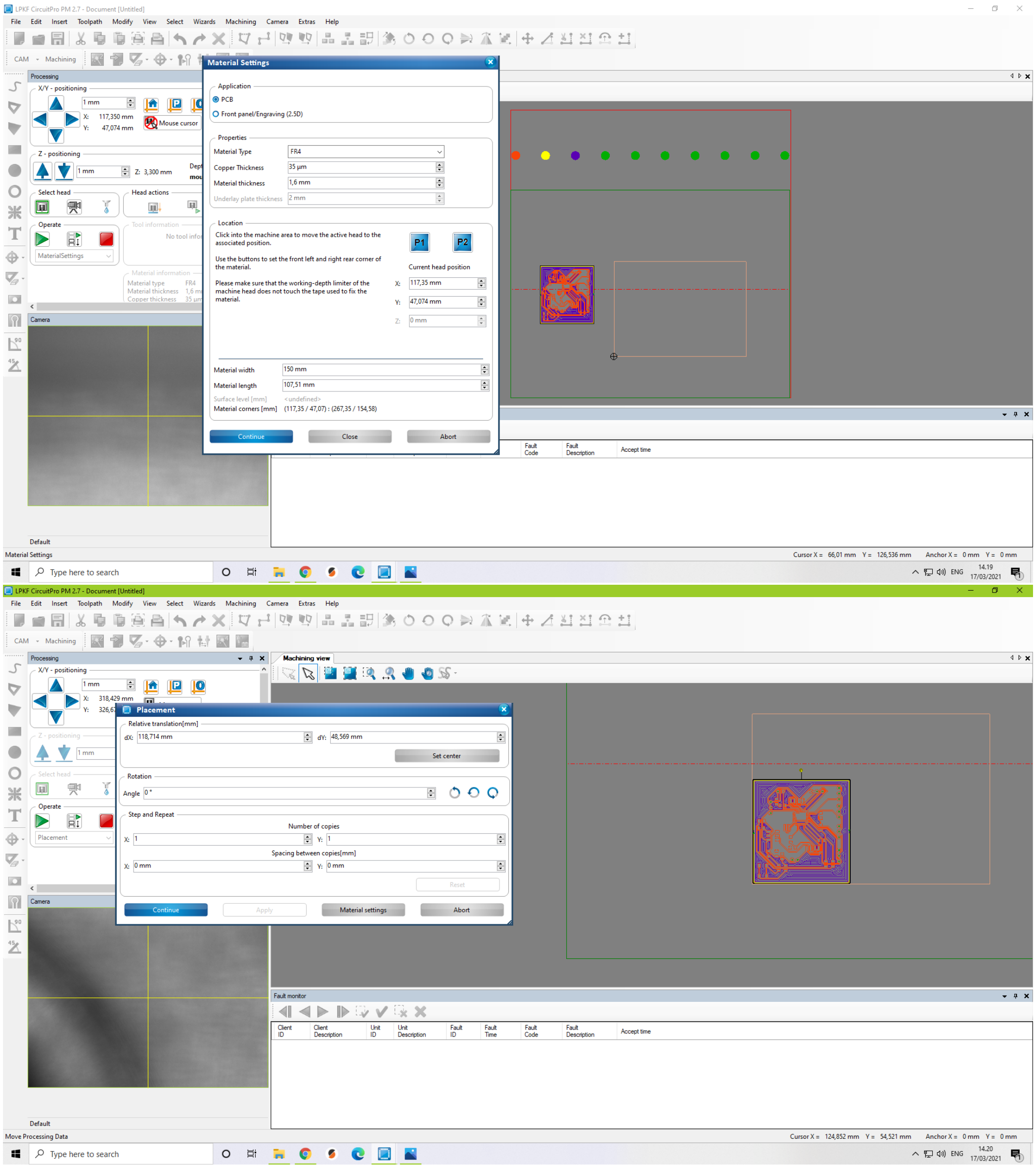
Holder ☐		Tool		Tool life spent
1 ☐	○	Universal Cutter 0,2 mm (60,16%)	✓	60,16%
2 ☐	○	Contour Router 1 mm (65,38%)	✓	65,38%
3 ☐	○	End Mill 1 mm (54,05%)	✓	54,05%
4 ☐	○	Spiral Drill 0,6 mm (1,27%)		1,27%
5 ☐	○	Spiral Drill 0,7 mm (0,35%)		0,35%
6 ☐	○	Spiral Drill 0,9 mm (0,20%)		0,20%
7 ☐	○	Spiral Drill 1 mm (5,70%)	✓	5,70%
8 ☐	○	Spiral Drill 1,1 mm (0,00%)		0,00%
9 ☐	○	Spiral Drill 1,3 mm (0,00%)		0,00%
10 ☐	○	Spiral Drill 1,5 mm (1,77%)		1,77%

Please use tool holder check-boxes to make these functions available.

Assign Tool to Tool Magazine

Cursor X = -182,764 mm Y = 288,117 mm Anchor X = 0 mm Y = 0 mm

Figure 25. a) Tool path b) Tools update



Material Settings

Application

● PCB

○ Front panel/Engraving (2.5D)

Properties

Material Type: FR4

Copper Thickness: 35 µm

Material thickness: 1,6 mm

Underlay plate thickness: 2 mm

Location

Click into the machine area to move the active head to the associated position.

Use the buttons to set the front left and right rear corner of the material.

Please make sure that the working-depth limiter of the machine head does not touch the tape used to fix the material.

Current head position

X: 117,35 mm

Y: 47,074 mm

Z: 0 mm

Material width: 150 mm

Material length: 107,51 mm

Surface level [mm]: <undefined>

Material corners [mm]: (117,35 / 47,07) : (267,35 / 154,58)

Placement

Relative translation[mm]

dX: 118,714 mm

dY: 48,569 mm

Rotation

Angle: 0 °

Step and Repeat

Number of copies

X: 1

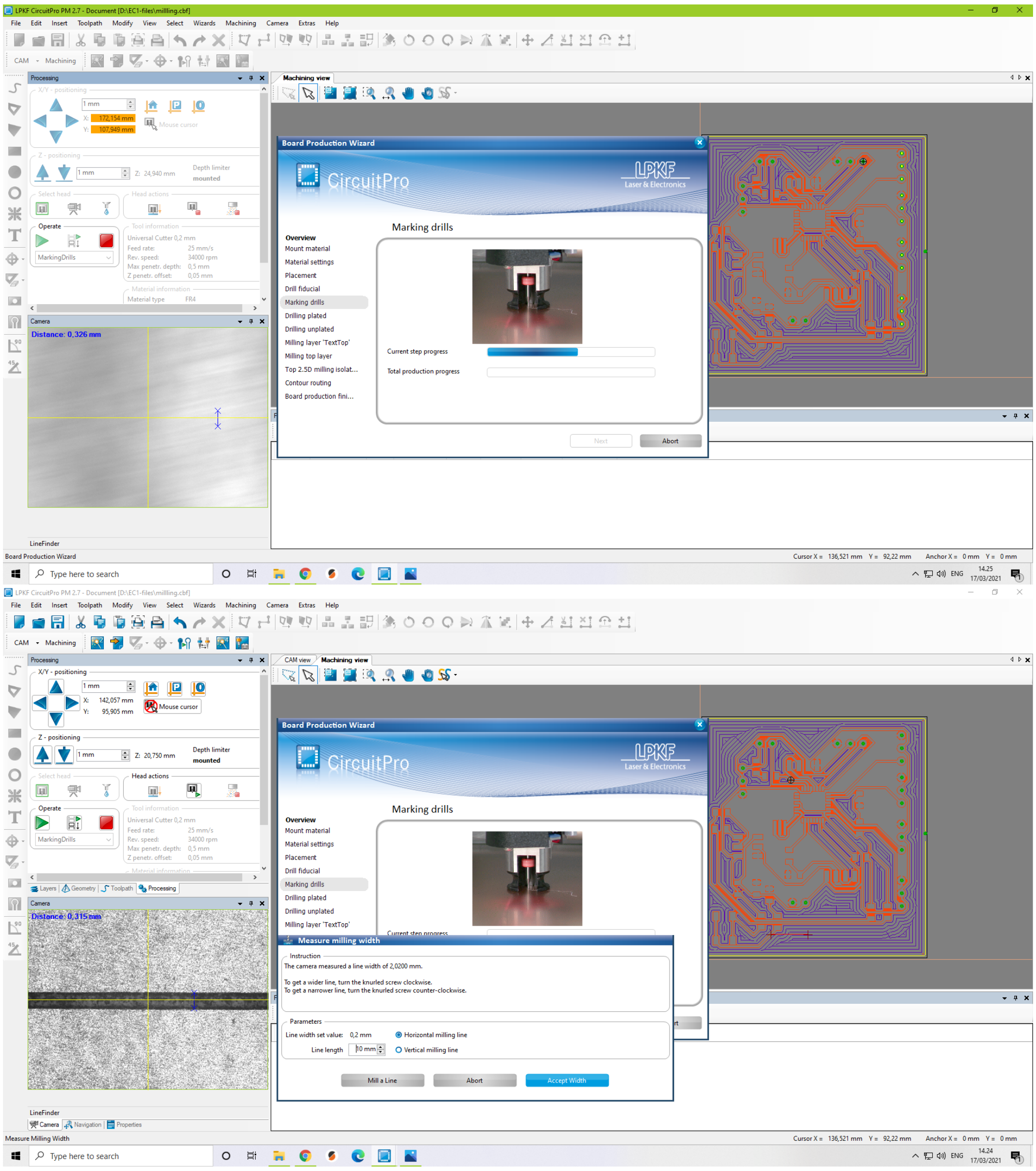
Y: 1

Spacing between copies[mm]

X: 0 mm

Y: 0 mm

Figure 26. a) Material settings b) Placement

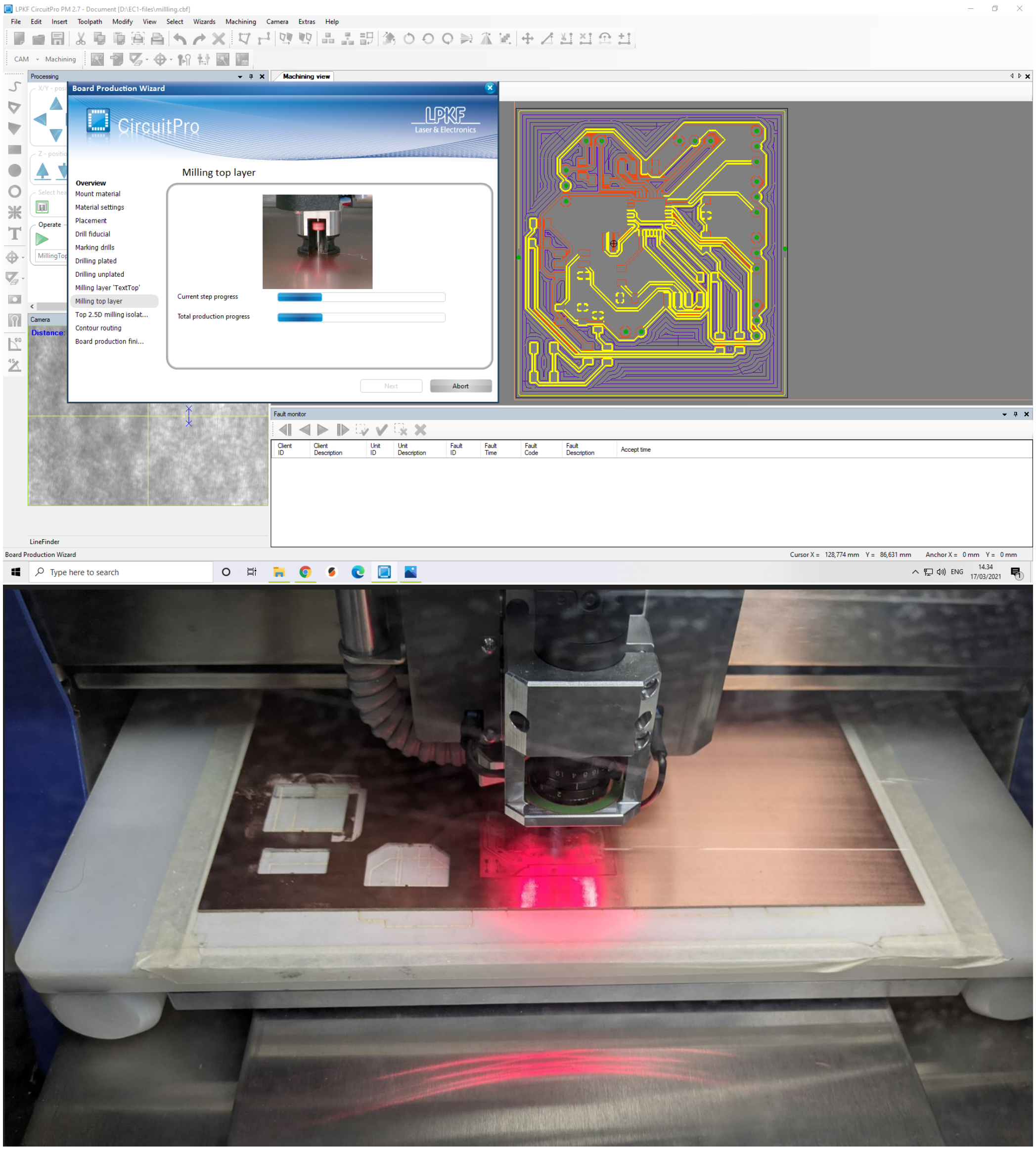


The camera measured a line width of 2,0200 mm.

To get a wider line, turn the knurled screw clockwise.
To get a narrower line, turn the knurled screw counter-clockwise.

Line width set value: 0,2 mm
Line length: 10 mm
● Horizontal milling line
○ Vertical milling line

Figure 27. a) Marking drills b) Mill a line



Cursor X = 128,774 mm Y = 86,631 mm Anchor X = 0 mm Y = 0 mm

Figure 28. a)Milling progress in the software tool b)Milling progress on the machine side.

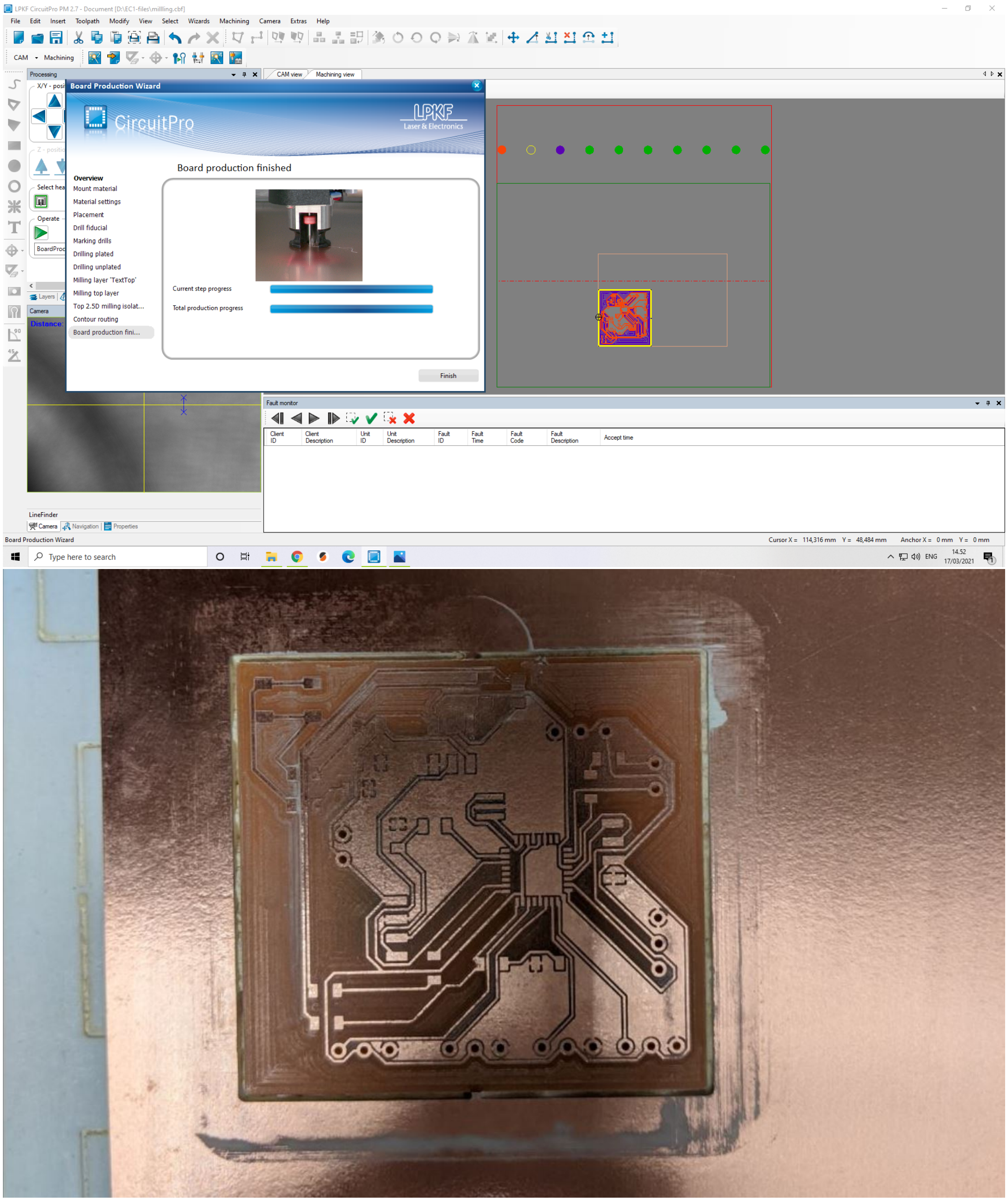


Figure 29. a)Board production Finished b) Board after milling

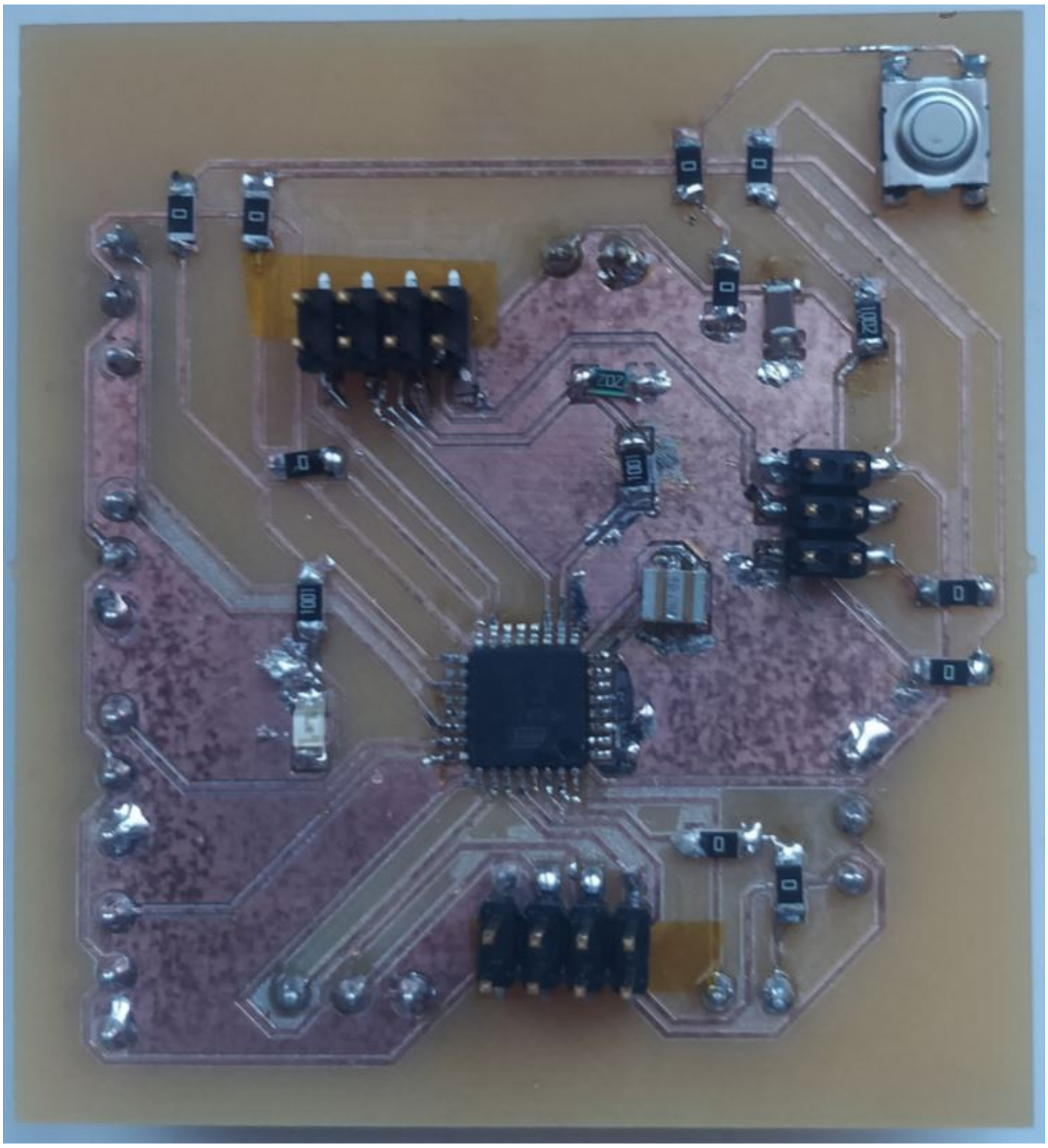


Figure 30. Final PCB board

This part describes the testing that was carried out to make sure that the board works. Prior to the milling of the PCB board, the soldering stage also involved a couple of testing and ultimately the final testing of the Final board.

During soldering, it's good to check for short circuits after every component is added because the board traces are so small that during soldering there could be short circuits in undesirable areas. The good thing about doing it after every component is that later on after the whole board is soldered you don't have trouble localizing a short circuit by going through all the soldered components. Moreover, ICs should be carefully soldered and tested for short circuits as their pins are too close to each other. Finally, power supplies should be tested thoroughly for short circuits and to identify voltage levels of the supply. All this is done using a multi-meter.

The following sections will in detail showcase burning the bootloader onto the processor and a simple program to check if the design works properly.

7.3. Burning Bootloader on the ATMEGA 328p Microcontroller

The aim of the design was to be able to program the board using Arduino IDE. For this, a bootloader has to be uploaded on to the Microcontoller's flash memory. To achieve this, a programmer board is necessary. For our application a USB tiny programmer shown in figure 31. The process goes as follows:

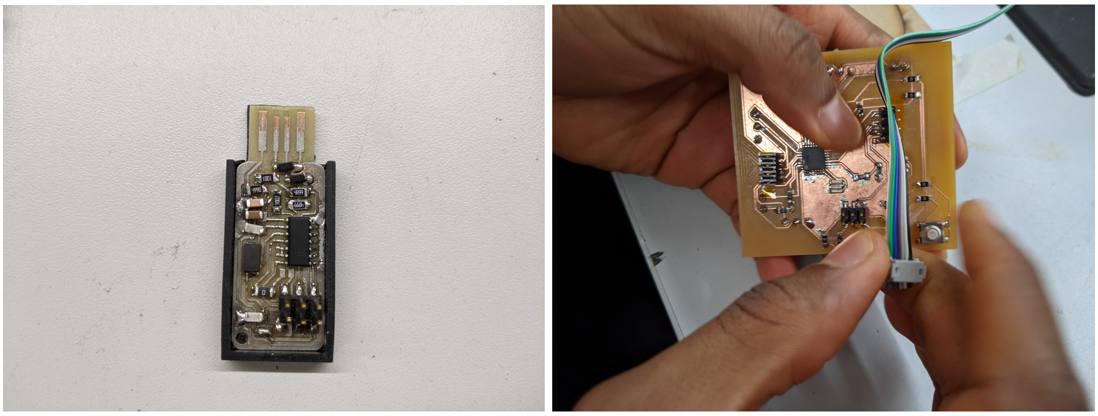
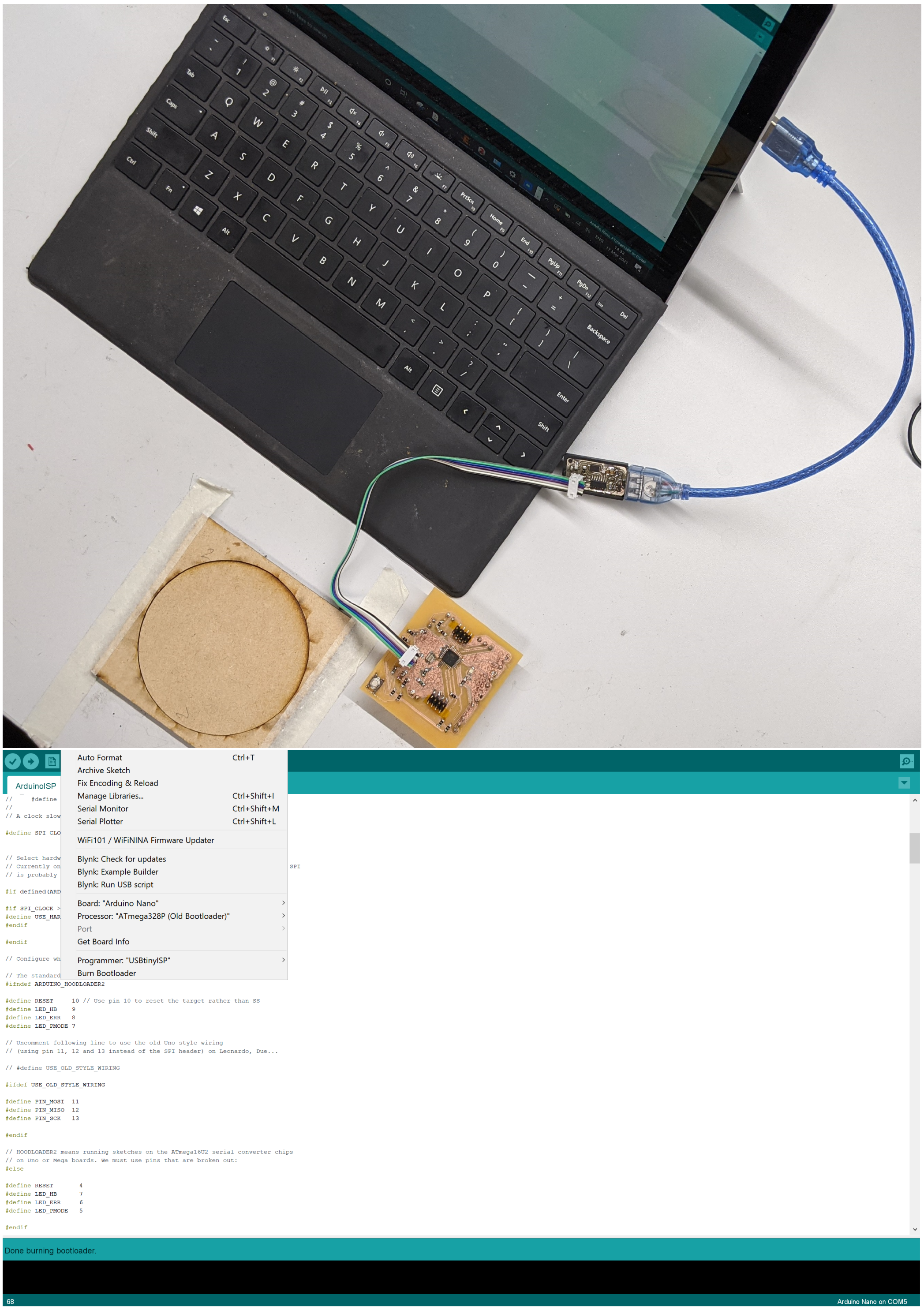


Figure 31. a) USB Tiny Programmer (the visible six pin are the SPI interface) b) Target Board(the visible six pin are the SPI interface)

First, Open the arduino IDE, Then connect the Programmer and Board's SPI ports(They are visible in figure 31) together as shown in figure 32 (a).After this, go to **tools** and make the configurations as shown in figure 32 (b) and select **Burn Bootloader**. If the process is a success it will show **Done burning bootloader**.

7.4. Simple LED Blinking Program Test

Now that the bootloader is successfully installed, let's test the board with a basic program to see if our design works. To do this the setup remains the same as previously discussed. Then go to **File>Examples>01. Basic>Blink** to get the LED blinking program (shown in figure33 (a)). Since we are still using a programmer to upload the program, by holding **shift key** the usual **Upload** button turns to **Upload using programmer** then press it till it shows **Done uploading**.Check the Board for the results, figure 33 shows the LED blink.



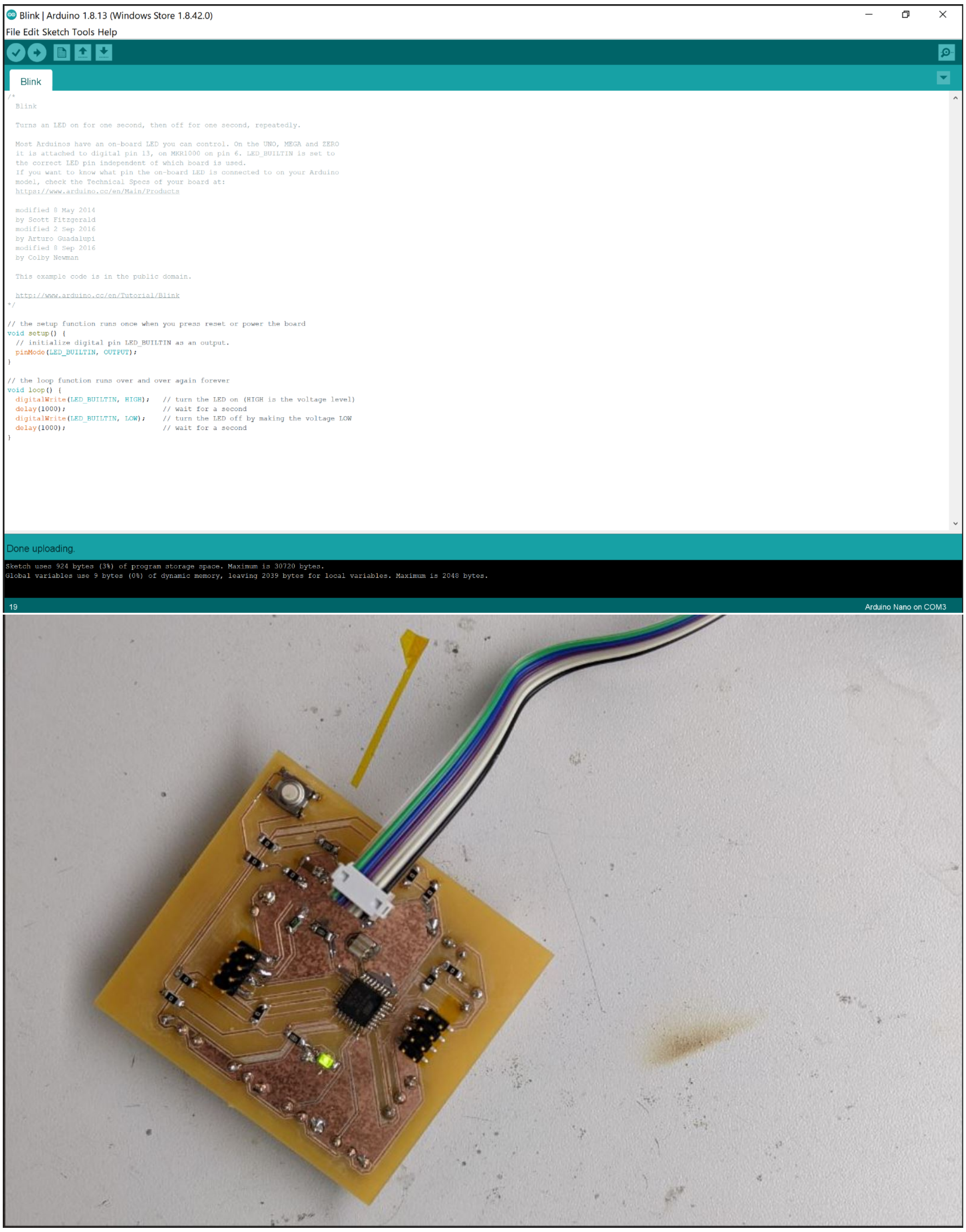
Board: "Arduino Nano"
Processor: "ATmega328P (Old Bootloader)"
Programmer: "USBtinyISP"

```
//     #define
//
// A clock slow

#define SPI_CLO


// Select hardw
// Currently on                                                     SPI
// is probably

#if defined(ARD

#if SPI_CLOCK >
#define USE_HAR
#endif

#endif

// Configure wh

// The standard
#ifndef ARDUINO_HOODLOADER2

#define RESET     10 // Use pin 10 to reset the target rather than SS
#define LED_HB    9
#define LED_ERR   8
#define LED_PMODE 7

// Uncomment following line to use the old Uno style wiring
// (using pin 11, 12 and 13 instead of the SPI header) on Leonardo, Due...

// #define USE_OLD_STYLE_WIRING

#ifdef USE_OLD_STYLE_WIRING

#define PIN_MOSI  11
#define PIN_MISO  12
#define PIN_SCK   13

#endif

// HOODLOADER2 means running sketches on the ATmega16U2 serial converter chips
// on Uno or Mega boards. We must use pins that are broken out:
#else

#define RESET      4
#define LED_HB     7
#define LED_ERR    6
#define LED_PMODE  5

#endif
```

Done burning bootloader.

68 Arduino Nano on COM5

Figure 32. a) Programmer Board setups b) Arduino IDE setting



```
/*
  Blink

  Turns an LED on for one second, then off for one second, repeatedly.

  Most Arduinos have an on-board LED you can control. On the UNO, MEGA and ZERO
  it is attached to digital pin 13, on MKR1000 on pin 6. LED_BUILTIN is set to
  the correct LED pin independent of which board is used.
  If you want to know what pin the on-board LED is connected to on your Arduino
  model, check the Technical Specs of your board at:
  https://www.arduino.cc/en/Main/Products

  modified 8 May 2014
  by Scott Fitzgerald
  modified 2 Sep 2016
  by Arturo Guadalupi
  modified 8 Sep 2016
  by Colby Newman

  This example code is in the public domain.

  http://www.arduino.cc/en/Tutorial/Blink
*/

// the setup function runs once when you press reset or power the board
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(1000);                       // wait for a second
  digitalWrite(LED_BUILTIN, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);                       // wait for a second
}
```

```
Sketch uses 924 bytes (3%) of program storage space. Maximum is 30720 bytes.
Global variables use 9 bytes (0%) of dynamic memory, leaving 2039 bytes for local variables. Maximum is 2048 bytes.
```

Figure 33. a) Program b) LED Blink