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Original scientific paper

MECHANICAL DESIGN OF A LOW-COST 3D PRINTED FOREARM PROSTHESIS WITH THE ABILITY FOR INDIVIDUAL FINGER CONTROL

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A b s t r a c t: The prosthesis technology has had a renaissance in recent years, although the improved and natural control coupled with fast and fluid movements have led to devices which are very expensive and not attainable by the majority of people who need them. In this paper we present a mechanical design of a low-cost of 3D printed forearm prosthesis which has the ability for individual finger control using a sophisticated software solution by incorporating artificial intelligence. By using two actuators for each finger instead of one we allow for more precise and robust movements of the prosthetic, and by using affordable yet high-torque servomotors we can keep the price low while offering performance similar to much more expensive devices available on the market. The use of 3D printing is also used in order to drive down the cost of the prosthesis, by implementing materials which are inexpensive yet light, strong and durable.

Key words; electric prosthesis; 3D printing; mechanical design; electromyography; artificial intelligence

МЕХАНИЧКИ ДИЗАЈН НА НИСКОБУЏЕТНА 3D ПЕЧАТЕНА ПРОТЕЗА НА ПОДЛАКТНИЦА СО СПОСОБНОСТ ЗА ИНДИВИДУАЛНО УПРАВУВАЊЕ НА ПРСТИТЕ

А п с т р а к т: Науката за вештачки делови на телото (протези) има доживеано преродба во последните неколку години, но подобреното и природно управување заедно со брзите и глатки движења доведе до уреди коишто се многу скапи и не се достапни за мнозинството на лица на кои протезите им се потребни. Во овој труд е предложен механички дизајн на нискобуџетна 3D печатена протеза на подлактница која има способност за индивидуално управување на прстите со примена на софистицирано софтверско решение базирано на вештачка интелигенција. Со користење на два актуатора за секој прст наместо еден се овозможуваат попрецизни и поробусни движења на протезата, а со примената на евтини сервомотори, кои се карактеризираат со релативно висок вртежен момент, се задржува ниската цена на уредот, а се обезбедуваат перформанси слични на многу поскапи уреди достапни на пазарот. Употребата на 3D печатење исто така се користи со цел да се намали крајната цена на протезата, бидејќи се користат материјали кои се евтини, а сепак лесни, јаки и издржливи.

Клучни зборови: електрични протези; 3D печатење; механички дизајн; електромиографија; вештачка интелигенција

1. INTRODUCTION

The difficult task of replacing a missing limb can make one properly understand the complexities of the human body. Throughout the ages, innovators have been attempting to use artificial limbs to replace lost natural ones. There are numerous prosthetic devices that are shown to be from ancient civilizations all around the world, exhibiting the development of artificial limb technology. The technological development of prosthetic limb design has been relatively gradual up until recently.

Prostheses have largely remained passive tools that provide limited control and mobility, although as time went on and technology improved, designs began to incorporate hinges and pulley systems as well as better materials. This resulted in the development of basic mechanical body-powered gadgets, for example, metal hooks that can open and close when a person bends their elbow. Recently however, there has been a significant improvement in prosthetic devices and the demand for completely functional prostheses is at an all-time high as the number of amputees worldwide continuously rises each year [1]. Although today there are more options readily available for amputees in the market, acquiring a fully functional prosthetic is still an expensive process. A recent technological advance in this field has been the introduction of 3D printers. 3D printers allow for a multitude of new possibilities as this device is capable of creating different objects using recycled plastics and biodegradable materials, which is not only cost-effective but also better for the environment [2].

While in the past the most advanced prosthetics which used hinges and pulley systems were able to achieve some level of control, they were still basic mechanical devices. The prosthetics that are available today have become electrical devices which focus not only on the physical aspects of the device, but also on the level and ease of control through complex biofeedback systems. Perhaps sometime in the future prosthetic devices will be even faster, stronger, and overall better than biological limbs. To be able to achieve this, the prosthesis should not only be able to perform the desired movement of the user, but also be durable, lightweight and easy to put on.

The goal of this paper is to present an easy to build artificial forearm prosthetic through the use of 3D printing, made from an adequate material which is strong and robust yet not too expensive. By using readily available low-cost materials we can design a prosthetic device which is not only easily controllable by the user but also costs less than the prosthetics that are already available on the market.

The paper is structured as follows: in Section 2 we discuss different types of prosthetic device which already exist but have flaws which we aim to improve upon thorough the research in this paper. Then, in Section 3 we present the mechanical design of the proposed prosthetic device and explain the design process of the model as well as the drive system which is used to actuate the fingers. In Section 4 we make a comparison between different types of materials for the 3D printing of the prosthesis in order to find the one which offers the best strength and durability. Finally, in Section 5, we close the paper by discussing the pros and cons of the presented solution and propose further possible ideas and improvements which can be implemented in the future.

2. RELATED WORK

A prosthetic device should ideally be as simple and effortless to use as possible. The prosthesis would not be helpful in any practical sense if the user has to struggle to perform even the most basic elementary movements, such as gripping and object or pointing. While there are multiple options for electrical prosthesis on the market, a fully functional prosthetic is either hard to find or unaffordable.

A functional prosthetic arm must be able to overcome various design and manufacturing obstacles. The degree to which the mechanical device replicates the human arm and the degree of mobility that it can provide are determined by the complexity of the mechanical and electrical systems which are implemented, which is also the reason they are usually highly priced. Many prosthesis on the market use electromyography (EMG) for the detection and measuring of electrical impulses in the residual limb of the user while particular flexions are performed [3]. By analyzing these measurements through signal processing or machine learning methods, one can extract the type of movement the user was trying to perform. An example of a myoelectric forearm prosthesis is shown on Figure 1.

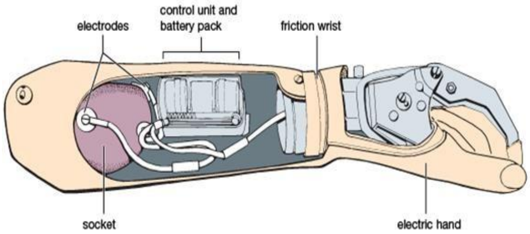

Fig. 1. Visual representation of a myoelectric forearm prosthesis [10]

There have been many successful attempts at classifying the movements carried out by users through the use of electromyography, although most fall short due to the use of multiple expensive EMG sensors [4], complex solutions that cannot be easily implemented in an embedded system [5, 6] , or a limited array of possible movements [7]. We have already addressed some of these issues in previous publications where we successfully achieved the classification of individual finger flexions using only two-channel electromyography with an F1 score of 91.3% [8], as well as individual and combined finger flexions with an F1 score of 96.6% [9].

In the early days of prosthetic arm development, the heavy weight of the device used to be a major problem which made most of the functions difficult to perform and even caused the user to feel uncomfortable due to having to carry the prosthetic for long periods of time [11]. The materials that were used were also inadequate as they absorbed sweat, which made the maintenance of such devices difficult. With the introduction of 3D printing, the whole outlook of the market eventually changed. Lighter materials were being used to create prosthetics and the cost was also able to be significantly reduced.

There is a large variety of prosthetic devices which can be categorized according to their method of operation. Simple, immobile devices known as passive prostheses are mainly used for aesthetic appeal and while they help amputees regain their confidence and normality in everyday life, these types of devices offer basic functionality and control, if any. A separate kind of passive prosthesis is a customized silicone restoration device that serves primarily as a cosmetic item. The transparent silicone glove can be painted to precisely match the user's skin tone, body hair, and other natural traits. This particular and thorough style of painting and design allow the prosthetic to have the look of a real arm, without any of the functionality. The simplicity of these devices usually means they are very affordable and inexpensive, which is the reason they are the most common option for amputees when choosing a prosthetic device [12].

Another type of prosthesis that is available is a body powered prosthetic device where the control is carried out through a harness fastened to the user. These prosthesis typically consist of a straightforward tool, like a mechanical hook, that is connected to the shoulder and elbow and moves along with them. Although these gadgets are very simple and offer very limited control, they continue to be a common type of prosthesis due to their lower cost [13].

In this paper we present an electric forearm prosthesis which is affordable yet offers high functionality through fast, easy and natural control by the user. The control of the devices is accomplished using electromyography with just two EMG sensors placed on the residual limb. The electrodes of the sensors are used to measure to electrical impulses when flexing the muscles which flex and extend the fingers of the hand. After being amplified, these signals are then transmitted to a microcontroller, which uses the data to analyze them in order to detect the desired movement, i.e. which finger (or fingers) the user wanted to flex or extend. When the movement is detected, the microcontroller sends a signal to the necessary internal actuators and carries out the movement on the prosthesis. Due to this complex system of measurement-classification-actuation, mechanical prostheses cannot be controlled to the same extent as myoelectric ones.

The main focus of the paper is the mechanical design of this proposed prosthesis and the different aspects considered while designing the device to be cost effective yet efficient and robust in terms of weight, usability and durability. The signal processing and control aspects have already been covered in [8] and [9], and the discussion on the mechanical considerations presented here represents the next step in the overall design of a low-cost fully functioning forearm prosthesis.

3. MECHANICAL DESIGN

Some of the current limitations of prosthetic arms available on the market today include:

- **Price** – not everyone who has the need for a prosthetic arm can afford it due to their high cost.
- **Robustness** – prosthesis are susceptible to damage and require frequent repairs and/or replacements.
- **Functionality** – currently existing prosthetic arms may not be as functional as minimally necessary for users to decide to use them in everyday life; in order to replicate a real human arm the functionality of the prosthesis must be fast and fluid and the implementation of sensory feedback, such as a feeling of touch, is also a needed but difficult task.
- **Comfort** – prosthetic arms are usually not comfortable to wear for extended periods of time and this can make the user reluctant to use them.
- **Weight** – depending on the material the prosthesis is made out of, the weight of the device also plays a major factor in the decision of the user to continue using the prosthetic.

The first and main focus of the mechanical design of the proposed prosthesis was to make it inexpensive to produce thus making it affordable for the majority of people who need it. Seeing as the majority of the cost of the prosthesis is driven by the material which is used to produce it, the first approach to making it affordable is the use of basic yet durable plastics and 3D printing. Although this can be achieved, there are a lot of aspects to consider while designing and building the device, such as the shape and geometry of the palm and fingers, the material of the mechanical joints, the actuators which will be used to carry out the flexions etc. Keeping these aspects in mind, as well as the previously mentioned flaws of current prosthesis, multiple iterations and designs for the prosthetic arm were created.

a) *Early ideas*

Before the process of designing the prosthetic arm, certain key decisions had to be made for the basis of the design, such as the actuation mechanism, the number of servo motors to be used and the placement of the motors in the prosthesis. It was decided initially that for the actuation, ten servo motors (two per finger) would be housed in the body of the prosthesis in order to increase the strength and efficiency of the flexions. Figuring out a way to house the actuators while also finding a way to implement the correct actuation technique proved to be a challenge during the initial steps of the design process. The locking of the coil was another important aspect to consider in prior to creating the model as, if not locked properly, the flexions would not be carried out smoothly and this would affect the functionality of the prosthesis.

It was decided that the best option for the actuation method of the fingers would be a basic pulley and string design which mimics the biological actuation of fingers through tendons present in a real human arm. The CAD model of the prosthesis was then designed using SolidWorks.

b) *Finger design*

Each of the four fingers is made up of three different printed parts that are connected using 3D printed pins. To produce a tendon locking point, the artificial tendon coils around the inside of the fingertip. This tendon forms a closed loop by navigating guide pathways inside the finger. All of the joints experience a rotational stress as the tendon is tugged by the servo motor, which causes the finger to curl up. As mentioned previously, in this design each finger has two tendon coils, one for the distal interphalangeal joint (DIP) at the fingertip, and another for the proximal interphalangeal joint (PIP) in the middle of the finger. It is crucial for each tendon to have a locking point in order to increase the efficiency of the spin or grip hold during flexion. If a locking mechanism is missing there is a possibility that the tendon would simply slip under tension, preventing the finger from moving. The extension of the fingers is done by applying tension to the other end of the tendon. It is necessary to use a high-quality braided string to ensure that it will stretch very little under tension. The final design of one of the fingers is shown on Figure 2.

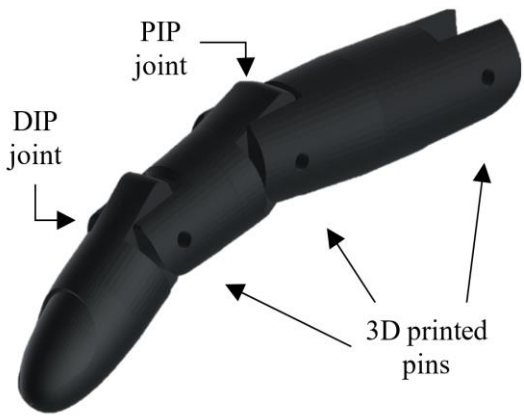

Fig. 2. Finger design concept for the artificial prosthesis

c) *Thumb design*

Due to the complexity of the movement of the thumb, its design was different in comparison to the rest of the fingers. The majority of commercial and research prostheses strive to offer at least two degrees of freedom for the movement of the thumb, and the same approach has been taken in this paper as well. Without considering the extension, the thumb is consists mainly of two parts representing the interphalangeal (IP) and metacarpophalangeal (MP) joint. In both parts a tendon lock is used for carrying out the flexions. As in a real biological hand, the thumb is the most integral part of almost every movement carried out by the hand as it is the locking finger in most gripping techniques. In order to optimize tendon orientation and avoid tendon lines becoming snagged on a sharp edge, guide holes have been integrated into the design of both the fingers and the thumb. The design of the thumb is shown on Figure 3.

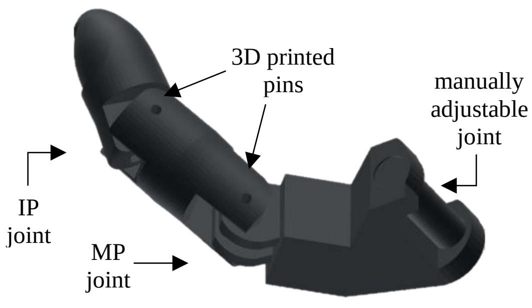

Fig. 3. Thumb design concept for the prosthesis

d) *Palm design*

Each of the fingers connects to the palm by using 3D printed pins. In this paper, the palm was the most redesigned part as initially the plan was to have two parts combining to form the body of the palm, where the main part was used to connect the thumb, index and middle finger and the other part was consisted of separate moving extensions for the ring and little finger. The two extensions would be fixed to the main part using screws. This design was initially considered for better grips, but due to the complexity in the design as well as the aesthetic appeal, the design was later changed in order to keep the palm as a single rigid part on to which the fingers would be fixed, as shown on Figure 4.

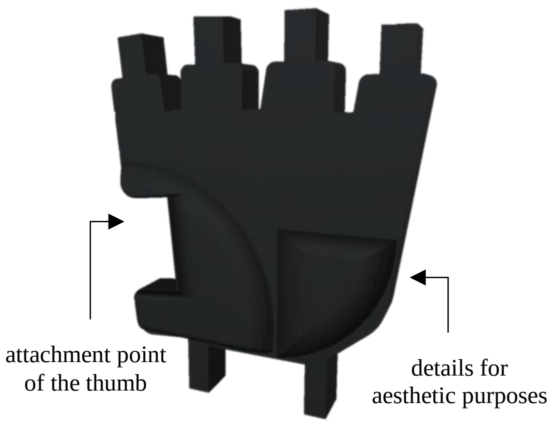

Fig. 4. Palm design concept for the prosthesis

e) *Forearm design*

Even though the forearm section contains no moving parts it is still a challenge to design as it needs to house most of the electrical components and actuators, as well as the power source for the whole device. After the complete forearm section was designed it was split into separate components which could then be assembled using screws. If the forearm was 3D printed as a single large component it would not be possible to place the servo motors and tendons inside the palm. A robust and durable material is necessary for the production of the forearm as the screws can easily break and crack weaker plastics, even though the guide holes for the which have been incorporated into the design have enough material to firmly support the screw. The two large sections of the forearm can be 3D printed as a single piece without affecting the assembly of the device, however most basic 3D printers are simply not large enough to print an object of this size. The final model of the forearm is shown on Figure 5.

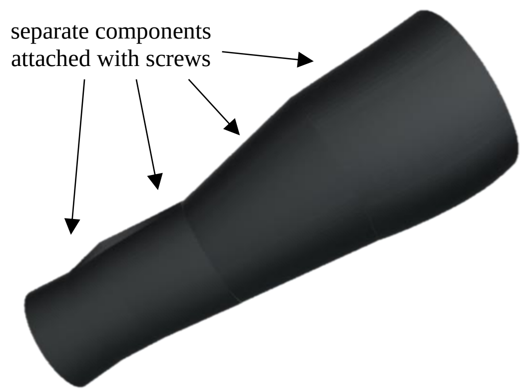

Fig. 5. Forearm design concept for the prosthesis

f) *Drive system*

As stated previously, the drive system of the proposed prosthesis is based on a biological actuation mechanism where the string is meant to mimic the tendons in the palm, while the servo motors, which are the driving force of the prosthesis, mimic the muscles. The string is pulled when the servo motor turns in one direction, flexing the finger. If the servo motor turns in the opposite direction, the finger will extend. An individual pulley is used to attach the thumb, index and middle finger. Each of the fingers has a separate servo motor system attached to it. The ring and little finger are joined to one pulley system due to the constrained space inside the palm. In a way this actually mimics the dependence of neighboring fingers in a real biological hand, so no meaningful functionality will be lost due to this simplification.

The actuators which are used for the movement of the fingers of the prosthesis are standard servo motors. These motors can be controlled to rotate to angular positions of up to ±90° from their initial position which is adequate for the small and limited range of motion of the joints of the fingers. Relatively inexpensive servo motors with sufficient torque and speed have been used in this system to maintain the low cost of the prosthesis. The use of higher quality servo motors would lead to an increase in finger strength and precision, but the exponential increase in cost is not worth the minimal improvement they would bring.

g) *Power supply*

It is of outmost importance that the prosthesis is fully portable and capable of multiple hours of constant use without the need for power by external sources. As such, an internal power supply capable of providing enough power for the whole device while lasting an adequate amount of time is required [14]. The servo motors are the main users of power in the system due to the significant amount of current which is necessary during operation. Disposable batteries would not be a good solution since the servo motors would drain power too quickly, meaning they would need to be replaced frequently. Lithium Polymer (LiPo) batteries offer a high energy density and are rechargeable, meaning they are a decent option for the task at hand, but they would need to be taken out of the prosthesis, recharged, and put back in on an almost daily basis, which can be a hassle for some users. In order to reprimand this, an alternative source of power was used, i.e. a power bank device, which can be easily recharged by connecting it to a wall plug by a regular USB-C cable. The power bank is housed on an exterior pouch on the forearm of the prosthesis, meaning it is easily accessible to recharge as well as replace when needed.

4. MATERIAL COMPARISON

When creating a 3D printed product one must consider the material that will be used, which depends on the type of product that is being created, the environment in which it will be used, as well as the price-to-quality ratio of the material. Three of the most popular 3D printing materials are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and nylon. They can all be extruded using a basic 3D printer and at their low price of around \$20–\$30 per spool, they are among the most affordable filaments available on the market today. When making a simple prototype which will not be used as a final product, the choice of material is usually between PLA and ABS, and nylon and its copolymers are often used when there is a need for a higher quality item. The comparison between these materials will be made using a simplified qualitative approach in terms of what is necessary for the task of this paper. A more detailed review of the materials can be found in [15].

4.1. *Polylactic acid*

Polylactic acid (PLA) is a user-friendly thermoplastic with a higher strength and stiffness than both ABS and nylon. The low melting temperature and minimal warping make PLA one of the easiest materials to 3D print successfully, which is the reason it is the most often used when prototyping new designs [16]. One of the drawbacks to using PLA is its low melting point, which causes it to lose almost all of its stiffness and strength at temperatures above 50° Celsius. In addition to that, PLA is also very brittle which causes parts to have poor durability and impact resistance, often virtually falling apart after a short amount of time. A comparison of the characteristics of this material is given in Table 1. Even though PLA is the strongest of the three proposed plastics, the poor chemical and heat resistance make it unsuitable for anything other than the initial printing of the prototype in order to tune the tolerances between the individual parts, as it is the cheapest and most widely available material to use.

Table 1

Characteristics of PLA

PLA	Bad	Good	Great
Strength	■	■	
Stiffness	■	■	
Durability	■		
Printability	■	■	■
Heat resistance	■		
Chemical resistance	■		

4.2. *Acrylonitrile butadiene styrene (ABS)*

Weaker and less rigid than PLA, ABS is a tougher and lighter filament which is suitable for applications that require somewhat higher quality products. This plastic is characterized with a higher durability, is about 25% lighter and has around four times the impact resistance compared to PLA. Seeing as ABS is more heat resistant and prone to warping, it is more difficult to 3D print [17]. It is necessary to have a heated bed for the 3D printer as well as an extruder which is able to get 40°–50° Celsius hotter. Even though ABS is not prized for its heat resistance, it still has superior heat deflection temperature in comparison to PLA and nylon. These characteristics, as shown in Table 2, make ABS the perfect option for printing the initial full prototypes of the proposed prosthesis which can be used to test the device, while still remaining a relatively low-cost option.

Table 2

Characteristics of ABS

ABS	Bad	Good	Great
Strength	■	■	
Stiffness	■	■	
Durability	■	■	
Printability	■	■	
Heat resistance	■	■	
Chemical resistance	■		

4.3. *Nylon*

In contrast to PLA and ABS, nylon is a flexible and durable material with less strength and stiffness. The signature malleability leads to an increase in toughness and an impact resistance that is ten times that of ABS. Nylon is also characterized with a surprisingly high chemical resistance which leads to it being used in more industrial applications. Similarly to ABS, nylon is more difficult to 3D print than PLA as it needs to be extruded at very high temperatures. It must also be kept dry before printing due to its tendency to soak up moisture from the air. The main downside to nylon in comparison to PLA and ABS is its lower strength and rigidity which makes in unsuitable for most serious applications. As a result, nylon is usually altered such that it is combined with other plastics in the form of a copolymer, but the best quality nylon filaments are usually a form of nylon-fiber mixtures.

Filled nylon is a type of mixture of nylon with tiny particles of a stronger material such as fiberglass or carbon fiber. The goal of these mixtures is to preserve the favorable flexibility and chemical resistance of nylon while adding a considerable amount of strength, stiffness, head resistance as well as making it easier to print [18]. A comparison between the characteristics of regular nylon and nylon filled with carbon fibers is given in Table 3 and Table 4. This type of filament is one of the best ones available on the market today, and while it is slightly more expensive than its counterparts, it is a great option for fully functional prototypes as well as end use products. The final version of the prosthesis is to be constructed using a mixture of Nylon PA12 and 20% carbon fibers which will result in an optimally resistant, strong and durable device.

Table 3

Characteristics of nylon

Nylon	Bad	Good	Great
Strength	■		
Stiffness	■		
Durability	■	■	■
Printability	■		
Heat resistance	■		
Chemical resistance	■	■	■

Table 4

Characteristics of filled nylon

Nylon + CF	Bad	Good	Great
Strength	■	■	■
Stiffness	■	■	■
Durability	■	■	■
Printability	■	■	
Heat resistance	■	■	
Chemical resistance	■	■	■

5. CONCLUSION

The initial idea of this research was to design and build a high quality forearm prosthesis from a strong, resistant and durable material which is inexpensive to produce and yet offers high functionality with natural control by the user. After multiple iterations of the design of the fingers and palm, a design that was satisfactory in both aesthetics and usability was created. Finding a design that can host ten servo motors was a challenging task, but with the extent of research and the approach of experimenting with different variables in the design allowed us to create a prosthesis that has double the power and precision in comparison to most prosthetic devices which use only one actuator per finger. Extensive research was also done on the material to be used for the 3D printing of the device, and finally it was decided that Nylon PA12 mixed with carbon fiber would be the optimal solution for the final product.

To ensure that the proposed prosthesis is able to be used in real-world situations for extended periods of time, certain aspects of the system still need to be tested and analyzed, such as:

Detailed and thorough testing of the strength, rigidity, heat and chemical resistance and overall durability of the finished prosthesis.

Design of a comfortable yet stable socket connection in order to better attach the device to the residual limb of the user.

Further improvements of the control system of the device and the classification algorithm, as well as expanding the range of possible movements.

Real-world trial studies using amputees to better ascertain the pros and cons of the proposed device in order to improve upon possible flaws that may have been overlooked.

In conclusion, the design for a low-cost myoelectric forearm prosthesis with the ability for individual finger control that was presented in this paper is a solid base for the production of an affordable yet functional device which can improve upon the lives of many people. After the completion and implementation of the aforementioned improvements, we can ensure that the device will be a strong contender in the market due to the innovative hardware and software approaches that were used in its creation, while also allowing it to be available to a larger number of people who have a need for it.

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