RecyGlass, A Low-cost System for Recycling Glass Bottles in a Distinctive Way

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Abstract. Traditional glass recycling processes exhibit difficulties when it comes to segregating carefully the glass material by type and color. Having this in mind, new recycling alternatives that avoid this stage in the entire process have arisen. Nevertheless, they are still dangerous for operators or novel users. To surpass both problems, this paper presents in detail the mechanical, electronic and control design and implementation of RecyGlass, a low-cost autonomous glass recycling machine with 6 different sub-systems: clamping, rotational, translational, cutting, polishing, and serigraphy. Real and 3D model images are used to present in a better way the design and result of the RecyGlass project in its different design levels. Finally, this work also analyses, in the conclusion section, the energy consumption of our alternative compared to traditional glass recycling processes.

1. Introduction

Environmental pollution is a matter of latent concern because of the consequences related to climate change, the depletion of natural resources, and the extinction of living beings. Therefore, waste recycling has appeared as a possible solution to this problem.

Despite the fact that many countries have encouraged waste treatment, the recycling rate of generated solid waste (GSW) is still low. This can be illustrated by the low recycling rates of solid waste that Europe, the U.S.A and Peru exhibited in 2016: 37.8 \% \cite{1}, 35.2 \% \cite{2} and 1.9 \% \cite{3}, respectively. One of the reasons that explains why these numbers remain low is that consumers do not have proper resources on hand to recycle in an easy way. Moreover, the authorities of different countries do not operate in an articulate manner to generate incentive recycling policies valid for different territories \cite{4}. To ease the recycling operation for the average user, many efforts have been made to conceive alternative processes to traditional recycling ones, especially for glass bottles (5 \% of GSW) \cite{4}.

It is important to note that in the traditional glass recycling process, the glass needs to be segregated carefully by both material and color. On the one hand, material segregation is required because certain kinds of glass such as ovenware, Pyrex, or crystal can cause production problems and defective containers \cite{5}. On the other hand, color segregation is necessary to ensure a final product with a specific shade of color \cite{5}, \cite{6}. An alternative to avoid material and color segregation is the transformation of glass bottles into different glass products without the melting process. This is especially important because the melting stage consumes the highest amount of energy (approximately 4.72 kJ/g) out of the 6.66 kJ/g that the entire process consumes \cite{7}. 

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In the literature review, there are some examples of machines designed to transform bottles without a melting stage, which implement machine learning algorithms [8] and the use of FPGA’s [9]. However, these machines only transform plastic bottles or metal cans because of profitable reasons [10]. In the case of glass bottles, there are not complete existing machines designed to transform them. Thus, companies like Green Glass [11] perform this process using a bench saw which could eventually cause severe damage to the operator. Additionally, DIY tools such as [12] are available to cut glass bottles; nonetheless, these are still dangerous in the sense that users manipulate these tools during the entire transformation process. In this light, this paper presents an innovative low-cost solution for transforming a glass bottle into a glass.

RecyGlass is an autonomous system that allows obtaining glasses with serigraphy designs from used glass bottles. This system can receive as an input round glass bottles regardless of the type or color of the glass material. RecyGlass performs a cutting process, followed by a polishing stage to soften the edges of the glass, and finally performs a serigraphy process to print different designs on the surface. All this transformation process is executed autonomously, the user only needs to feed the machine with glass bottles, press the start button, and wait for the glass to be ready. Even more important, Recyglass represents a safe alternative for operators, since they will not be exposed to cuts or glass dust.

This document describes the design and implementation details of the first functional prototype of RecyGlass in the following organizational structure: Section 2. analyses the design and manufacturing of the system based on 2.1. the logic of the system, 0. the description of the main subsystems, and 2.3. the electronic design. Section 3. presents preliminary tests and results. By last, Section 4. lists the conclusions of the present work.

2. Design and Development of the system
The design of RecyGlass considers the following requirements:

- Incoming glass bottles must have a diameter between 65 and 90 mm without labelling and embossing.
- The system must have a maximum operating time of 12 minutes per bottle.
- The dimensions of the system should not exceed 1.5 (L) x 1 (W) x 1 (H) m.
- The electronic components must be inside an enclosure with a minimum rating of IP55, according to IEC 6052 standard.
- The system must have an enclosure to prevent glass dust from coming out of the working space of the prototype and for general safety.
- The electronic components should work properly between 0° and 30°.

Figure 1 shows the final design of the system, and Table 1. presents its main specifications.

| Specification   | Value         |
|-----------------|--------------|
| Total length    | 0.82 m       |
| Total width     | 0.72 m       |
| Total height    | 0.72 m       |
| Material        | AISI 6061    |
| Weight          | 60 kg        |
| Input energy    | 220 VAC – 60 Hz |

2.1. The logic of the system
As soon as the operator turns RecyGlass on, all variables and GPIO’s restart to the initial setup. After this, all the actuators move to a pre-defined home position (Position A in figure 2). Then, the user should insert the bottle and press the start button, the system clamps the bottle and the cut process starts. When
the cut process finishes, the system removes the top half of the bottle, and the remaining half is moved to the polishing and serigraphy area in point B (Figure 2). After those processes, the polished glass with a serigraph design moves back to the initial position (Position A in Figure 2). The user should remove the final product and press the end-process button. Then, if required, the user will be able to insert another bottle.

Figure 1. Implemented system.

Figure 2. CAD model of RecyGlass subsystems: 1) Clamping, 2) Rotational, 3) Translational, 4) Cutting, 5) Polishing and 6) Serigraphy Subsystems.

2.2. Description of the subsystems

RecyGlass consists of different subsystems with specialized tasks. Figure 2 shows the location of these subsystems.

2.2.1. Clamping subsystem. This subsystem is responsible for holding the bottle after it enters. The bottle remains clamped during all the processes: cutting, polishing, and serigraphy. After the entire transformation process finishes, RecyGlass releases the final product and the user can remove it. This subsystem is able to determine the bottle diameter during the clamping process. The clamping mechanism consists of a 3-jaw chuck [13] with HDPE extensions. The subsystem uses a stepper motor with a 5:1 gearbox reduction to drive the jaws. RecyGlass uses a hall sensor and a magnet to detect a complete turn of the base. It also uses them to determine the bottle diameter. Apart from that, the subsystem uses another hall sensor and magnet to detect when the chuck is completely open. In this way, the machine can determine both the bottle diameter and the moment when the bottle is completely held by the clamping mechanism. Figure 3 shows the subsystem configuration.

2.2.2. Rotational subsystem. This subsystem controls the bottle’s rotational direction and speed during the cutting and serigraphy processes. This subsystem uses an axial bearing, a belt, two pulleys, a chuck, and a stepper motor to transmit power. The Arduino UNO controls the subsystem using the TB6560 driver.

2.2.3. Translational subsystem. This subsystem controls the translational motion of the clamped bottle from stage to stage. The subsystem has a synchronous belt transmission with a stepper motor, bearings, and a couple of pulleys to transmit power.

2.2.4. Cutting subsystem. This subsystem uses three glow plugs to cut the glass. The structure of the cutting subsystem has three parts: a glow plug holder, a mobile base, and a vertical backrest. The structural material of the subsystem is acrylic PMMA, according to NBR-ISO 7823-2. Furthermore,
bakelite rods are used as thermal insulation elements. Figure 4 shows the 3D model of the cutting subsystem.

When the cutting process starts, the rotational subsystem turns the bottle gradually both clockwise and anticlockwise. After two minutes, a horizontal crack appears on the surface of the bottle, which indicates that a thermal shock has occurred. This subsystem was designed taking into account important properties of the different glass materials to obtain the most symmetrical and horizontal possible cut (according to the UNE-EN ISO 7459 standard). Some of these properties are wall thickness, impact resistance, resistance to vertical compression, and resistance to thermal shocks.

2.2.5. Polishing subsystem. This subsystem uses a rotational mechanism, which consists of a DC motor, a mechanical chuck, and a polisher. The polishing subsystem performs vertical movement thanks to the combination of a stepper motor and a T8-trapezoidal screw. A limit switch detects the maximum available displacement of the structure. Figure 5 shows the 3D model of the polishing subsystem.

2.2.6. Serigraphy subsystem. This module prints a personalized design with a permanent marker on the glass. Additionally, it prints the capacity of the glass in mm$^3$. This subsystem allows a 2-axis movement
by using a stepper motor and a T8-trapezoidal screw. It also consists of a servomotor and a 3D-printed holder made of PLA to perform the serigraph printing. Figure 6 shows the model of the serigraphy subsystem.

The serigraphy subsystem uses an adaptation of the open-source G-Code parser and CNC milling controller, GRBL [14]. This permits drawing any figure stored on a micro SD card. However, it is necessary to generate a specific G-Code for each new image before turning on the machine.

2.3. Electronic Design

Figure 7 shows the electronic architecture of the system. RecyGlass has an Arduino Mega as a master microcontroller that uses a state-machine logic. The states represent the six subsystems described above. The Arduino Mega controls the translational subsystem and decides which one should work. Depending on the state, it communicates with two slave Arduino UNO microcontrollers using UART communication. One of them controls the clamping, cutting, and polishing subsystems; and the other one, the rotational and serigraphy subsystems.

Each microcontroller generates PWM and digital signals to drive and control the speed and direction of the rotation of the motors. Besides, they can handle analog and digital signals coming from the different sensors allocated in each subsystem.

The user interface takes into account allowing the user to supervise the machine at each stage. The master microcontroller receives a digital activation signal from the start button. The finish button sends also a digital signal, and the operator must press it when the transformation process of a bottle finishes. There is also an emergency button that disconnects the energy source from the outlet. Additionally, two LEDs indicate the condition of the machine; when RecyGlass is waiting for a new bottle, the green LED is on, and when it is working, the red LED is on.

The outlet energy provides 220 VAC at 60 Hz. Switching and ATX power supplies transform the alternating voltage into continuous voltage. The 5 V-switching power supply is connected to the processing unit, the user interface, the sensors from the subsystem, the stepper motor drivers, and the relays. On the other hand, the stepper motors, their drivers, the DC motor, and the relay receive energy from the 12 V-switching power supply. Finally, each of the glow plugs receives energy from the ATX power supply because of the high current that they require.

Figure 7. Electronic architecture of the system.
3. Implementation and results
In this section, preliminary tests, the experimental setup and results are presented. It is important to mention that RecyGlass is a low-cost system built with a budget of 1000 USD.

3.1. Preliminary tests
These tests allowed us to carry out some modifications. For instance, during the cutting process, it was identified that the glow plugs needed to be perfectly aligned in order to obtain a uniform cut. If the glass rim obtained from the cutting process is not uniform, the polishing will not perform correctly and it may fail during the process.

Another aspect to take into account was the rotational movement of the bottle during the cutting process. While it is convenient to have a continuous rotational movement until the bottle is completely cut, it was not possible to implement this because the wires would have gotten tangled. Thus, to avoid this problem, the clamping chuck was programmed to rotate 2 revolutions clockwise, and 2 anti-clockwise, until the cut of the bottle was finished.

Finally, the linear speed of the translational subsystem was determined through several tests in order to allow a fast movement from point A to B and vice versa, keeping the clamped bottle still. Likewise, the rotational speed of the rotational subsystem was determined to allow a proper cut and an acceptable serigraph drawing. These parameters are presented in Table 2.

| Parameter                  | Value   |
|----------------------------|---------|
| Translational speed        | 0.1 m/s |
| Cutting rotational speed   | 0.5 rad/s |
| Serigraphy rotational speed| 0.4 rad/s |

3.2. Experimental setup
A sample of 10 different 85-mm-diameter glass bottles with an average wall thickness of 2.6 mm were tested. The setup included a video camera to get the amount of time of every process, and a DC-current clamp meter to measure the current consumed by the components of each subsystem. The total energy consumption of RecyGlass was determined using the supply voltage and current of all the electrical and electronic components, and the operating time provided by the camera.

3.3. Results
The tests performed in RecyGlass with the 10 different bottles lasted in average 10 minutes, which can be approximately extrapolated to a 6 bottles per hour processing capacity. The bottleneck of the entire process was the cutting operation, which lasted approximately 4 minutes (almost the 40 % of the full process). Energy wise, it was found that the system consumed in average a total amount of energy of 144.33 kJ/bottle (0.328 kJ/g), and the subsystem that required more energy was also the cutting
subsystem, 47.89 kJ. Most of this energy was consumed by the three glow plugs located in this subsystem, which each require 4 amperes to reach around 1000 °C. The average operating time and energy consumption for the ten tests are presented in Table 3.

To illustrate the overall process, a sample of photos of the most representative operations are presented as follows: Figure 8 shows the exact moment when the bottle is cut. The spout of the bottle is pulled by the glow plugs to the ramp, which at the end has a recipient to store these remains. Figure 9 presents the stage of the polishing process where the polisher is in contact with the in-process glass. Figure 10 shows the stage of the serigraph process where the pen is pressed against the bottle. The input bottle and the final product of one of the tests can be seen in Figure 11.

| Subsystem    | Operating time (s) | Energy Consumption (kJ) |
|--------------|--------------------|-------------------------|
| Clamping     | 22.2               | 14.77                   |
| Cutting      | 242.1              | 47.89                   |
| Polishing    | 155.4              | 18.22                   |
| Serigraphy   | 175.2              | 15.97                   |
| Translational| 17.8               | 23.91                   |
| Rotational   | -                  | 22.99                   |
| Electronics  | -                  | 0.58                    |
| **Total**    | **612.7**          | **144.33**              |

4. Conclusion and future work

We have presented the design and implementation of the first functional prototype of RecyGlass. The autonomous design of the system avoids the dangers of manipulating the in-process glass, and of inhaling glass dust coming out of the cutting and polishing stages. We have also noticed that the use of this prototype represents a less consuming alternative to the classic recycling options: 0.328kJ/g 6.659kJ/g .100 = 4.9 % of the total energy consumption of typical glass recycling processes (for more details see the introduction and results sections). Furthermore, color and material segregation is not required to obtain a final product of acceptable quality level. The design of RecyGlass comes with no scalability or replicability restrictions. Future work will elaborate on reducing the operating time and increasing the quality level of the final product. To do this, the configuration of the cutting subsystem needs to be redesigned to focus even further on the heat applied on the bottle. In the same way, a laser will be implemented to obtain a better resolution on the serigraph designs.
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