Intelligent Automation And Soft Computing, 2019
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Vol. 25, no. 3, 441–449
https://doi.org/10.31209/2018.11006161

Design and Implementation of an Intelligent Ultrasonic Cleaning Device

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ABSTRACT

Ultrasonic cleaners are devices that perform ultrasonic cleaning by using ultrasonic converters. Ultrasonic cleaners have been employed to clean dirty and rusty materials such as optic, jewelers, automotive and dental prosthesis sectors. Due to non-identified correctly cleaning time, cavitation erosion has been occurred at some materials, which desire for cleaning. In this study, an intelligent cleaning device that runs autonomously identified cleaning time, saves energy, and makes the cleaning process safely has been designed and implemented. An ultrasonic cleaning time has been adjusted automatically by monitoring of turbidity and conductivity values of liquid that is put in to the cleaning tank. Thus, the process cleaning has been achieved without cavitation erosion by the developed device. In addition, energy and time consumptions have been lowered by the intelligent algorithm defining the cleaning time.

KEY WORDS: Cleaning, Digital signal processing, intelligent control, Pulse inverters, Ultrasonic transducer array.

1 INTRODUCTION

THERE are many cleaning methods used in various fields of industry. Some of these are acid cleaning, vapor degreasing and washing method using high pressure liquids. However these methods can damage the material to be cleaned and they also can damage to the environment together. Safety risks, toxicity of certain solvents and presence of solvent residues in target compounds coupled with low extraction yield have stimulated interest in developing environment-friendly (green) extraction technologies, which can minimize or eliminate the use of organic solvents (Tiwari, 2015). Today, those environmentally friendly methods are being developed in the cleaning industry (Lanin and Tomal, 2015). One of these methods is the Ultrasonic Cleaning Method (UCM). Ultrasonic cleaner is commonly used for cleaning dirty and rusty materials at the optical, jewelry, automotive and dental prosthesis sectors.

As a matter of fact, UCM has been widely increased speed in critical cleaning applications and has been used to improve the cleaning effectiveness of alternative chemicals (Fuchs, 2002). Ultrasonic cleaning equipment consists of a boiler filled with cleaning fluid, a piezoelectric converter forming cavitation bubbles in the liquid and a signal generator that drives the converter. The dirty material is inserted into the liquid and then signal generator with converter begins to produce cavitation bubbles. As a result of bursting of these bubbles on the material by hitting the dirty surfaces lime, rust and the others are ensured to be away quickly from the surface of that material. The liquid used in the process must be clean. As the liquid becomes dirty, the amount of the produced bubbles becomes less.

In this study, an intelligent ultrasonic cleaning device is designed and implemented. During the cleaning process, the dirty material immersed in the liquid changes the turbidity and conductivity of the cleaning liquid. Cleaning time of the process is controlled intelligently by measuring the liquid turbidity and conductivity as different from the studies on this field. The cleaning process is stopped either the material is completely cleaned or the liquid has no cleaning property any more without a need of an operator by analyzing the liquid manner. The aim of this study is to increase the cleaning efficiency and so decreasing the cavitation erosion and preventing unnecessary energy consumption. A probable damage on the surface of the material to be cleaned would be prevented by ending the cleaning process without giving any opportunity for operator errors. As this

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study prevents much time which spent by operators for cleaning process at the same time it automates the cleaning process thorough the newly developed intelligent algorithm embedded the microcontroller.

2 RELATED WORKS

ULTRASONIC Cleaning Device (UCD) has been widely used to clean materials for several decades. Ultrasonic cleaning has been researched extensively. This cleaning method is used for various application fields and consequently solution of the problems encountered in the process, the effects of different materials on the process and the results of the process have been studied and analyzed in literature. The factors effective in cleaning materials in ultrasonic cleaning method are quite a lot. These are summarily cleaning fluid, temperature, standing waves, power, and frequency (Mason, 2016). However, the size, shape and made material of the tank, the ultrasonic transducers used, type and size of cleaned material affect the cleaning process in ultrasonic cleaning.

Fluid type plays an important role for the effectiveness of an ultrasonic cleaner (Niemczewski, 1980, 2007). Tzanakis and the others compared water and liquid aluminum for cavitation and they saw that, the highest cavitation activity was obtained for the lowest sonotrode tip amplitudes in water. Below the sonotrode, the cavitation intensity in liquid aluminum was found to be four times higher than in water (Tzanakis et al., 2015).

Niemczewski checked how the shape of cavitation-temperature plot during cooling was influenced by; frequency of ultrasounds, ultrasounds power density and, degree of air content in water. The experiments proved that anomalies on cavitation-temperature plots, observed in practice during cooling of thermally degassed water in the form of maxima in various temperatures, were caused by secondary regassing of water during its cooling (Niemczewski, 2014).

There are studies on design of power circuits, controller and finding the optimum operating frequency for ultrasonic cleaning devices. Tangel and the others designed an FPGA-based controller card to find the resonance operating frequency of the ultrasonic cleaning device (Yakut et al., 2009). Athira and the others used solar panels as power supply of ultrasonic cleaning equipment and the system power was 58W. Their system frequency was selected as 28 kHz to reduce the size of resonant components and thereby to reduce the voltage stress. Their design reduced the losses due to switching and thereby increased the efficiency of the system as 80.45% (Athira and Deepa, 2014). Basa and the others carried out a system for ultrasonic transducer by designing amplifiers in different frequencies to enhance the performance and the cleaning effect high but reduce the power losses to minimum. They aimed to clean fabrics with this system (Basa et al., 2012).

Some works on ultrasonic cleaning contains cleaning different material types. Kan and the others investigated the effect of ultrasonic cleaning of polytetrafluoroethylene (PTFE) membrane fouled by precoagulated humic acid-bentonite mixture. They found that ultrasonic cleaning was very effective in cleaning membranes fouled by cake formation but not those of pore blocking and the effectiveness of this membrane cleaning technique depended on the intensity and duration of ultrasound irradiation and the location of the cavitation zone relative to the fouled membrane surface (Kan et al., 2016). Verhaagen and the others showed the advantages of using an ultrasonic horn to clean the surface of small parts and holes more effectively. They introduced a Cleaning Challenge Device design to be used for the universal evaluation of cleaning performance of different equipment or processes, and specifically for ultrasonic baths. They put forth a positive effect in the removal of support material with relevance for the 3D printing objects (Verhaagen et al., 2016). Nguyen and the others used ultrasound to clean turbine engine oil filters effectively in ships, with ultrasonic devices having a frequency of 25 kHz and different powers of 300 W and 600 W, respectively. The effects of temperature, ultrasonic cleaning times, and pressure losses through the oil filter, solvent washing, and ultrasonic power devices were investigated. In addition, the cleaning efficiency of three modes (hand washing, preliminary washing and ultrasonic washing) were compared to assess their relative effectiveness. They saw that after each cleaning, microscopic observation indicated that no damage had been done to the filter surfaces during the high intensity, low frequency (kHz) ultrasound treatments. In addition, the reduction of pressure loss through the oil filter reached maximum levels with longer ultrasonic irradiation. Consequently, ultrasound-assisted oil filter washing was effective, requiring a significantly shorter time than manual washing (Nguyen et al., 2016).

Occurrence of cavitation is the other study field on ultrasonic cleaning. Baoji and the others detected the occurrence of cavitation in the cleaning device with a measurement method by aluminum foil. The area assessment method for the corrosion degree of the aluminum foil were put forward, which evaluate the cavitation’s strength by the proportion of the aluminum foil lost area taking in the total, and evaluate the distribution uniformity of small holes by the variance of corroded-area ratio of many small pieces. This measurement can provide an effective data support and experimental verification to the performance parameters design of the ultrasonic cleaning machine (Baoji et al., 2011). Other study is conducted research on the ultrasonic cavitation corrosion test results of the glazed wire (Zhang et al., 2011). During cavitation, there is very efficient and highly nonlinear conversion of acoustic energy to mechanical motion. The frequency spectrum produced by the oscillating cavitation bubble includes a fundamental frequency, harmonic, and sub-harmonic frequencies. When the cavitation bubble collapses, a broadband spectrum is produced (Xu et al., 2016). Yusof and the others studied physical and chemical effects of acoustic cavitation. They also discussed the effect of ultrasonic frequency and surface activity of solutes on the sonochemical degradation efficiency. They demonstrated that the physical effects could be used to enhance the flux of ultrafiltration membranes and deactivate pathogens present in aqueous and dairy solutions. The chemical effects generated during acoustic cavitation could be effectively used to degrade organic pollutants in aqueous environment (Yusof et al., 2016).

When reviewing the literature on this field, it is proven that there is no study on controlling the duration of the cleaning process. In this study, cleaning time of the process is controlled intelligently by measuring the liquid turbidity and conductivity. Consequently, this study makes up this deficiency.

3 HARDWARE IMPLEMENTATION

IMPLEMENTED intelligent (UCD) consists of a fluid tank, an ultrasonic transducer, an inverter and fluid analysis circuits. The liquid tank of the device is selected from steel material. An ultrasonic transducer was placed at the bottom surface of the tank so as not to affect other parts of the device.

Full-bridge inverter circuit for driving the ultrasonic transducers was implemented. The conductivity and turbidity sensors measuring the duration of the cleaning process was placed in the cleaning tank. These sensors send data to the controller circuit. The duration of cleaning process is determined with expert system in the controller circuit. A block diagram of the system is shown in Figure 1. The picture of implemented UCD is shown in Figure 2.

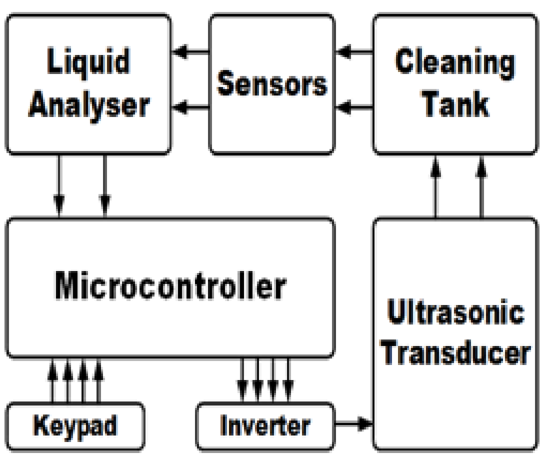

Figure 1. The Block Diagram of the UCD

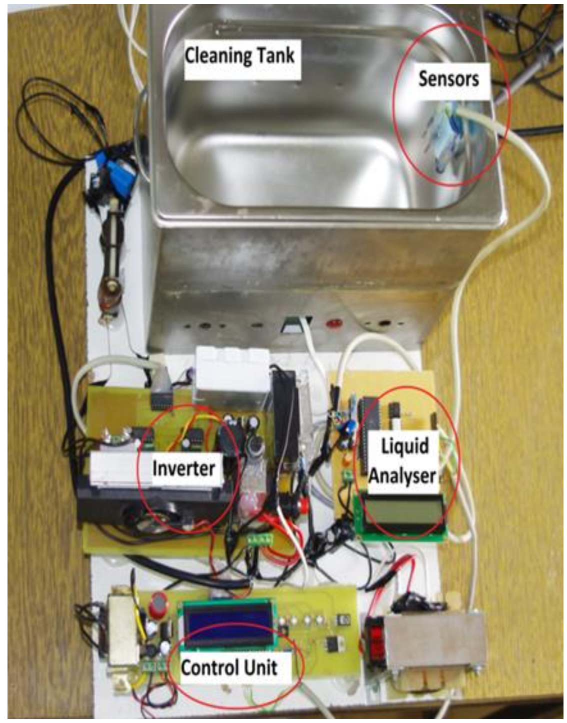

Figure 2. Picture of the Ultrasonic Cleaner Device

High frequency inverter was designed for drive transducer to generate the cavitation bubbles. Voltage Source Inverters (VSI) have been commonly used in industrial applications (Bowes and Clark, 1992; Ursaru et al., 2009). Inverters are varied depending on the shape and used areas (Handley and Boys, 1992; Holtz et al., 1993). In this study, inverter was designed as a square wave switching and H-bridge. The designed H-bridge inverter is seen in Figure 3.

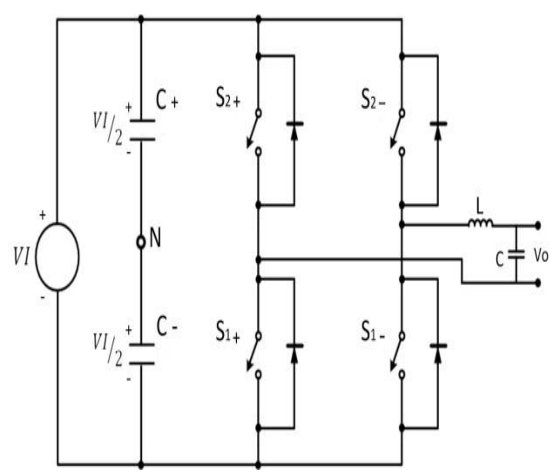

Figure 3. Full Bridge Inverter Circuit

The parameters of the designed inverter were determined with reference to the catalog information of the transducer used. The ultrasonic transducer works with a switching frequency of 38 kHz and peak voltage value of 450V. When generating the switching frequency, a 3μs dead time was used to avoid switching losses in the arms of the H-bridge inverter and short circuit.

The states of H-bridge inverter switching are given in Table I. At state 1, the positive cycle has been occurred by the S1+ and S2- switches at output. At this time S1- and S2+ switches are OFF positions. At state 2, S1- and S2+ switches are ON positions and S1+ and S2- switches are OFF positions so that the negative cycle has been occurred at output. At state 3, S1+ and S2+ switches are ON positions and S1- and S2- switches are OFF positions for to be Zero of output voltage so that sinusoidal AC voltage has been obtained at output.

Table 1. H-Bridge Inverter Switch State

	Switch State		Output Voltage
State	ON	OFF	VO
1	S1+/S2-	S1-/S2+	V
2	S1-/S2+	S1+/S2-	-V
3	S1+/S2+	S1-/S2-	0
4	S1-/S2-	S1+/S2+	0

Operating frequency of piezoelectric transducer is adjusted by the microcontroller. High-power MOSFETs used in H-bridge inverter circuit are driven by the MOSFET drivers. Ultrasonic transducer operates at high frequency conversions and the inverter used operates at 38 kHz frequency. The voltage applied to the transducers is obtained from the H-bridge inverter and the transformer with a conversions ratio of 1:1.5.

The power and the operating frequency of the switching elements were chosen in accordance with the transducer. The inverter was controlled by the PWM method. In this method, each switch was operated separately. The dead time was added between the ON- OFF times of two serial switches. Thus, time switching losses were reduced and the sudden high current flow was prevented in the system. The switching signals and the dead time are shown in Figure 4. The sine wave shape has been obtained at desired frequency with LC filter connected to inverter circuit output. Converters placed in the bottom of the washing tank constitute cavitation bubbles in the liquid. The size of the resultant cavitation bubble is inversely proportional to the operating frequency of the converter used. As the cavitation bubbles formed by high frequency converter are smaller whereas those formed by the low-frequency transducers are greater (Niemczewski, 2014).

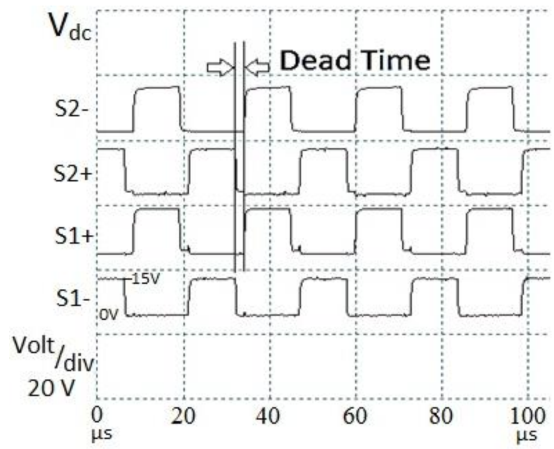

Figure 4. Dead Time and PWM

AC voltage obtained at the inverter output is unlike a full sinusoidal wave. So that an LC filter was designed to be a sinusoidal wave. Sinusoidal voltage obtained through filtering results is shown in Figure 5.

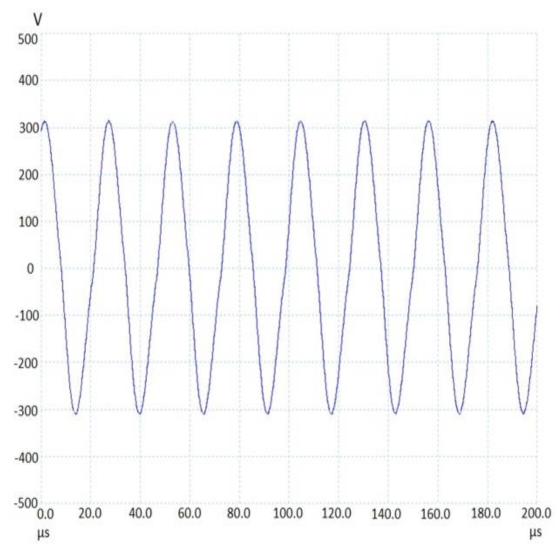

Figure 5. Output Waveform of H-Bridge Inverter

In ultrasonic cleaning systems, the increases in the temperature affect cavitation positively (Niemczewski, 1980). Therefore it is important to control the liquid temperature of the designed system. It is possible to heat the liquid with the boiler by placing heating resistants' on the side surfaces of the cleaning boiler. Getting the desired temperature was provided by measuring the boiler temperature with the temperature sensor which connected to the first microcontroller control card. The resistances were kept open until the fluid temperature reaches the set value with the code written on the microcontroller control unit. Then, when reached the desired temperature, resistances were closed and the desired temperature of the liquid in the cleaning tank could be kept constant.

The fluid resistance was measured with the metal rods by immersing into the cleaning liquid. Voltage was applied to the rods by the voltage divider resistor. Depending on the fluid resistance, a voltage drop was obtained on the rods. This voltage value was measured by connecting the analog input of the microcontroller. A simple conductivity measurement circuit of the cleaning fluid is shown in Figure 6.

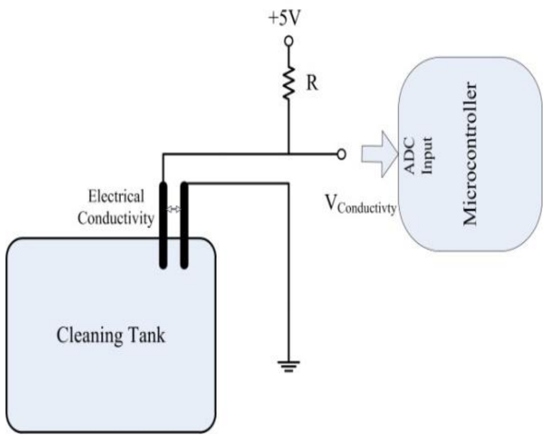

Figure 6. **Cleaning liquid conductivity measurement circuit**

It can be controlled with the aid of this circuit whether there is liquid in the cleaning tank. Hence, operating of the device without cleaning fluid can be prevented. Other fluid analysis sensor is an optic sensor that measures the amount of turbidity. The turbidity value of the liquid was measured by optic sensor to the liquid through interpreting the amount of light sent from the transmitter to taken from the receiver. The turbidity measurement circuit of the cleaning fluid is shown in Figure 7.

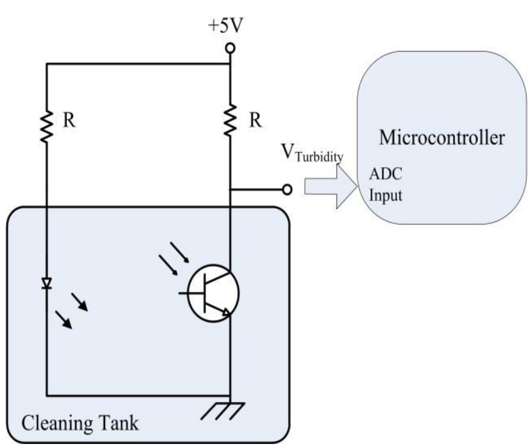

Figure 7. **Cleaning Fluid Turbidity Measurement Circuit**

The turbidity and conductivity values were sent to the second microcontroller. Fluid analysis circuit is the final circuit of the cleaning process.

4 SOFTWARE IMPLEMENTATION

TWO software`s have been embedded to the implemented ultrasonic cleaning system. One of them includes inverter and temperature control algorithm. Also it measures temperature, conductivity and turbidity and sends data to another for decide to running period. Another microcontroller either decides the cleaning process or runs on user interface. The flow diagram of the implemented system is shown in Figure 8.

It decides to a cleaning period when changing of liquid properties. Also, it runs when the microcontroller algorithm's checks the fluid changes. Additionally the microcontroller adjusts the length of cleaning time by controlling the liquid solution. Before the system is operated, firstly it is necessary to check whether there is liquid in the tank or not. If the tank is not filled with liquid, this means the system is overloaded and this may cause damage to the generator circuit and converters.

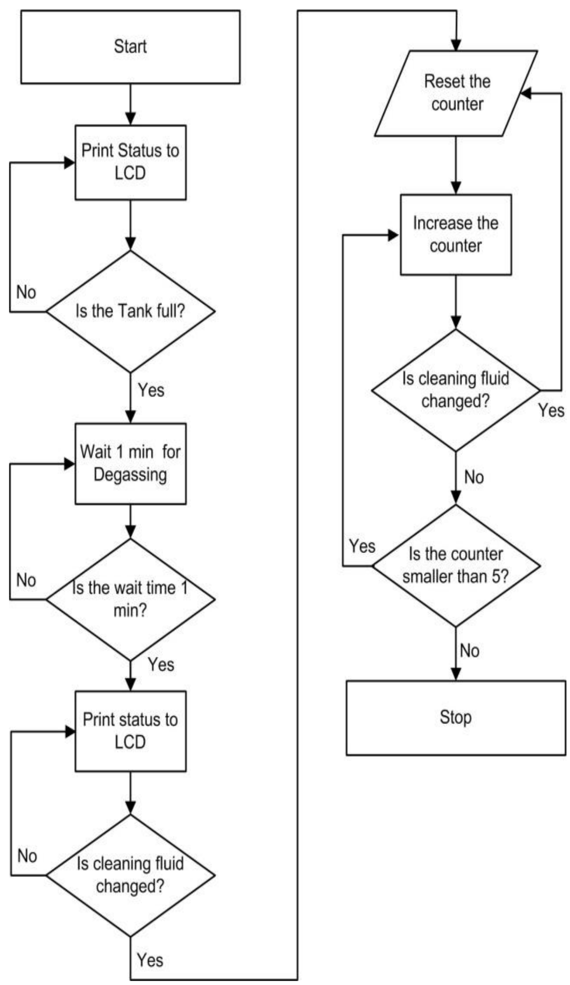

Figure 8. **The Flow Diagram of The Implemented System**

The intelligent algorithm of the UCD is shown in Figure 9. The implemented UCD system will not work if there is no liquid. In this way, ultrasonic transducers and generators will be protected.

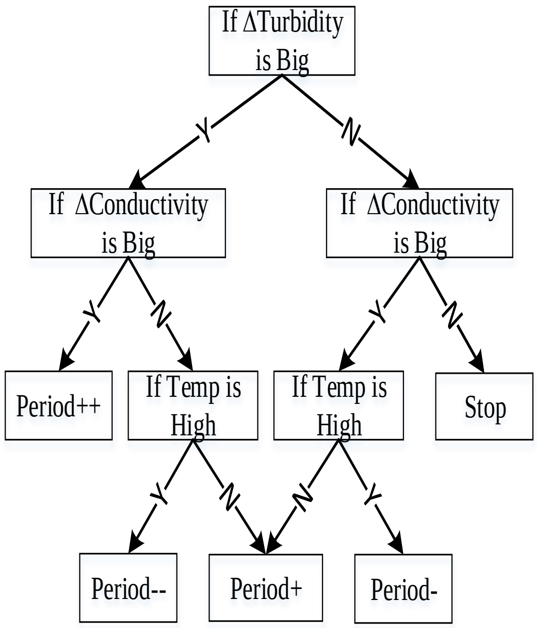

Figure 9. **Expert System of UCD**

The fluid-filled system carries out the gas removal process during the first one minute period. In this way, it makes the cleaning liquid ready for cavitation (Niemczewski, 2009). Changes in the liquid are examined after the dirty material is thrown into the liquid and then the decision about the running of the system is sent to the controller. The conductivity of the liquid and its turbidity change when the dirt on dirty equipment begins to be dissolved into the liquid. When these changes are stable after a certain time, the microcontroller controls this stability. Meanwhile if there become some changes in the liquid, the microcontroller waits for the fluid changes to be fixed again. The system turns itself off automatically if there isn't any change for the five times in succession.

5 EVALUATION

WITH the aluminum foil, it is possible to test the implemented UCD while creating cavitation bubbles. When the cavitation bubbles cause deformation on the surface of the immersed aluminum foil in the liquid that indicates that the device is functioning. Aluminum foil surface used for the test purposes is shown in Figure 10.

In conventional UCD, it is necessary to increase the continuity of the amount of cavitation in the cleaning tank in order to achieve the desired results. The amount of dirt in the liquid increases for a certain period and then it begins to prevent cavitation. In this point, either the dirty liquid should be changed or the strength of system should be increased. When excessive force is used the life of the ultrasonic transducer is reduced, at the same time the intensity of cavitation in the cleaning tank increases and also damages the material. This leads to cavitation erosion. With designed intelligent UCD, it became possible to clean contaminated materials without causing cavitation erosion.

Figure 10. **The Surface of Aluminum Foil**

In this study, pollution and turbidity of the liquid in the cleaning tank shows some changes during the cleaning process and the cleaning time is calculated by interpreting the expert system. The before and after states of the cleaned geared part is shown in Figure 11. The cleaning process was performed by immersing the geared part into cleaning tank.

The system completes automatically the cleaning process by examining the changes in the turbidity and the level of conductivity of the liquid. In the fluid analyzer, repeatedly if it is not changed five times during the cleaning, the cleaning process is terminated. The value of this counter can be increased to remove the immense dirt if desired.

Figure 11. **The Before and After States of The Cleaned Geared part**

The graph of data obtained during the cleaning process is given in Figure 12. Turbidity and conductivity values vary with the start of the cleaning process. During the process, if there is no change in the turbidity and conductivity values at the same moment the cleaning process is terminated. Dirt on the surface of the material dissolves throughout the cleaning process and it cause large changes in conductivity and turbidity values. Dissolved dirt sometimes affects the conductivity value, sometimes it affects the turbidity value. As the amount of dirt on the surface of the material being cleaned increases, the cleaning time is prolonged. The strongly bonded dirt on the material surface also prolongs the cleaning time. During the cleaning process, solvation of dirt on the cleaned material caused continuous change in the conductivity and turbidity values in experiment 1. During the measurement, sudden peaks occurred in the graphic because of the undissolved solid contact to sensor. At time t1, weakly bonded dirt on the material surface is broken off. Broken dirt caused a steep slope. Since the solid on the surface of the material to be cleaned is easily soluble dirt, continuous changes are observed in the cleaning fluid over time t2. In the case of strong bonded dirt on the surface, it is expected that there will be more flat slopes on the graphic. Since there is not much change in the conductivity and turbidity values at time t3, the cleaning process is terminated.

When looked at the cleaning time in experiment 2, the amount of the dirt, which is bonded weakly, is less than in experiment 1. Because of that, sudden changes through the cleaning process are not seen much. At the beginning of the cleaning process (t1), weakly bonded dirt dissolves and causes changes in the conductivity level. While at time t2 strongly bonded dirt is trying to hold on to the surface, at the end of t2 dirt broken off from surface cause large change in the conductivity. Since no major changes occurred at time t3, the cleaning process is terminated.

At time t1 in the graph of experiment number 3, weakly bonded dirt on the material surface dissolves. It is understood from the steep gradient in the level of conductivity that weakly bonded dirt dissolves quickly. Dissolved solid dirt changes the conductivity and turbidity of the cleaning fluid. At the time of t2, the strongly bonded dirt is dissolved from the material surface. The strongly bonded dirt is separated from material surface for longer time, because of this, the change in conductivity and turbidity level is smaller. During this time, detailed cleaning of the material is being done. There is no change in the cleaning fluid at time t3. Conductivity and turbidity values remain constant during this time. Conductivity and turbidity values are expected to remain constant for the end of the cleaning process.

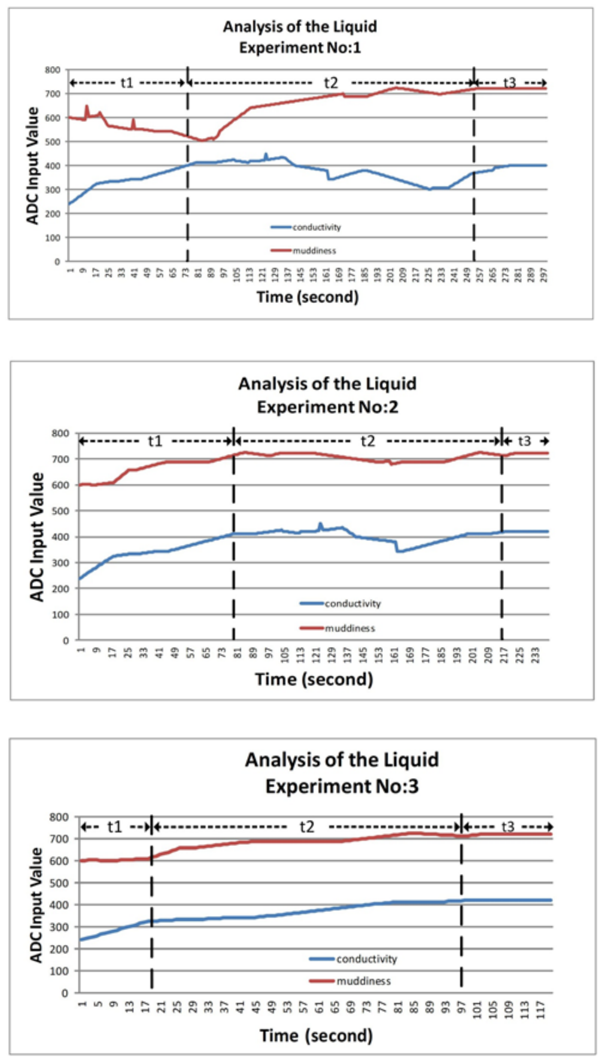

Figure 12. **The changes values of turbidity and conductivity in the cleaning processes**

In the graphs, the time intervals t1, t2 and t3 are indicated by dashed lines. These time periods vary depending on the recess ledge of the material surface and the solution effect of the cleaning liquid. The undissolved dirt particles near the sensors used in the measurement cause sudden fluctuations in the graphs.

The results of experimental studies are also given in Table II. The type of cleaning liquid affects the cleaning time. Likewise, the amount of the cleaning liquid temperature increases the cleaning process period and the cleaning performance.

The optimum temperature point is determined as 70 °C (Niemczewski, 2014). Dirty materials used in the experiments are greasy, dusty and rusty items. The dirty particles broken from the item which is cleaned in the cleaning liquid causes immediate changes in turbidity and conductivity values.

Table 2. The result of experimental studies

Experiment No	Temperature	Cleaning Liquid	Time(sec)
1	20°C	water	302
2		gasoline	241
3		soapy water	123
4	40°C	water	237
5		gasoline	205
6		soapy water	117
7	70°C	water	155
8		gasoline	75
9		soapy water	92

6 CONCLUSION

DURING cleaning a material, the liquid pollution and turbidity in a cleaning tank are an important factor defining the cleaning process time. In the study, the cleaning process time was decided by an intelligent algorithm embedded a microcontroller in reference to the pollution and turbidity. When compared with a conventional UCD’s, the working time of UCD was reduced about 20% at 20°C and 50% at 70°C by the newly developed intelligent algorithm. Moreover, the waste power and time consumptions were decreased. With the help of the intelligent UCD, the device carried out the contaminated materials without causing cavitation erosion unlike the conventional UCD’s.

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8 DISCLOSURE STATEMENT

NO potential conflict of interest was reported by the authors.

9 NOTES ON CONTRIBUTORS

Fecir Duran received the Ph.D. degrees from Department of Electronics and Computer Education, Gazi University in 2008. He is currently working as an Assistance Professor at the Gazi University Department of Computer Engineering, Faculty of Engineering, Ankara, Turkey. His research interests include embedded systems, power systems, artificial intelligent based algorithms, optimization based algorithms and Engineering Education.

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