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Steering system using variable capacitor and Arduino microcontroller for experimental engineering course

[1]Takuo Sakon, [2] Daiki Tochio, [3] Yuto Nakano

[1]Professor, Dr. of Science, [2]Student, [3]Student
[1,2,3] Mechanics and Robotics course, Faculty of Advanced Science and Technology, Ryukoku University,
Seta Ooemachi Yokotani 1-5, Otsu, Shiga Pref., 520-2194, Japan

Abstract : In this article, an experiment of the steering mechanism using a capacitor and the microcontroller is suggested as a theme for engineering experiment subjects at the university. In this work, we devised a steering system using a variable capacitor, microcontroller (Arduino UNO R3), and stepper motor. A purpose of this article is to learn the functions of the electronic parts (capacitor, inductor, resistor, diode, FET transistor), which are used for this mechanism while students make a rotation angle sensor in the engineering experiment. Using these elements, students can make various filters which are the signal transmission or decrement circuit, and a FET amplifier. Furthermore, they learn about programming and a principles of the microcontroller and stepper motor. The constitution of this system is, an oscillator and the rotation angle detection mechanism consisting of variable capacitor, and the drive mechanism consisting of microcontroller and stepper motors. The oscillator used in this circuit was not a commercial oscillator. AC sine wave was generated by means of an IC (LTC1799) which oscillated a square pulse, and RLC band-pass filter. A variable capacitor was used for the rotation angle sensor. A resistor was combined with this variable capacitor, and together, these constituted the high-pass filter with a CR circuit. The input AC signal of this circuit was changed by turning the knob of the variable capacitor. As the input signal to microcontroller was DC, we made the circuit which converted the amplitude of the output AC from a variable condenser into DC using bridge diode and RLC low-pass filter. The DC signal was input to an analog terminal of the microcontroller, and the stepper motor connected to the microcontroller was rotated. The rotation angle of the stepper motor was proportional to the rotation angle of the variable capacitor.

IndexTerms **- rotation angle sensor, variable capacitor, microcontroller, band-pass filter, high-pass filter, low-pass filter, stepper motor, steering system.**

I. INTRODUCTION

Recently, not only the basic experiment for scientific study of the physical law, but also the experiment using a PC or microcontroller is carried out by the enginerring experiment for science and technology studies system university students [1]. In some articles, it is written about a enginerring education experiment using the microcontroller. Shoaib *et al*. performed a simple Arduino-based experiment, which was designed to examine the acceleration of the object during free fall and to calculate the value of "*g* " (acceleration due to gravity) [2]. Organtini designed a engineering experiment of the time dependence of the voltage across a capacitor in an RC circuit as measured by a Arduino UNO board, which was connected to an RC circuit [3]. Sari *et al*. designed a engineering experiment using Arduino microcontroller platform to study temperature dependence of electrical resistance and to define the temperature coefficient for a conductor [4] .

In this article, an experiment of the steering mechanism using a capacitor and the microcontroller is suggested as a theme for enginerring experiment subjects at the university.

In the industrial world, energy saving, resource saving, the reuse of resources, and the use of natural energy are necessary in meeting the sustainable development goals (SDGs). Reducing the weight of motor cars is one of the problems. As for the steering system of a car, the angle of the front wheel is changed by use of a knuckle arm attached to the front wheel via a steering rod, electric power steering, a steering gear box (rack and pinion gear), a horizontal stick, and a tie rod. The total mass of the mechanical steering system made up of these rods and gears is dozens of kilograms. A rotation angle sensor is installed in the axis of the steering wheel, and we can contribute to reducing the weight of the car by removing the mechanical steering system. An electrical signal proportional to the angle of rotation is output to the steering motor. We developed a steering system with a novel rotation angle sensor using the super magnetostriction ferromagnetic alloy Terfenol-D [5], and a rotation angle sensor was developed using the capacitance method for the purpose of simplification and reducing the weight of the steering system of the car [6,7]. It is convenient to use a microcontroller and stepper motor in connection to these angle sensors to steer a car [8].

Capacitive sensors have the advantages of fast dynamic responsiveness and high sensitivity, and can be widely used in scientific and engineering measurements of angle [9-14], displacement [9], and force/torque [11]. Rotation angle sensors based on the capacitance method have been developed by many researchers [8-11]. Li et al. developed a smart capacitive angular-position sensor with a full-circle measurement range [11]. Fu et al. developed a capacitance angle sensor with a concentric ring multi-layer differential [12]. Qin developed a non-contact capacitive angle sensor [13]. Through the capacitance convertor-integrated circuit CAV424 and voltage–current convertor AM402, the signal of capacitive sensor is converted into a standard industrial current output from 4 to 20 mA. Fulmek et al. developed a capacitive sensor for relative angle measurement [14]. The relative angle between the two rotor-plates and the absolute positions of the rotor blades are calculated from the measurements of the capacitive coupling between different transmitting stator segments and a single receiving electrode.

In some articles, a mechanism using a stepper motor with an Arduino microcontroller [8] has been reported [15-24]. In reference to these articles, we devised a steering system using an Arduino microcontroller and a stepper motor. In this study, a variable capacitor was provided for the rotation angle sensor, because the output voltage of a variable capacitor is greater than that of a magnetostriction sensor. As the output voltage of a bridge circuit is around 20 mV, when using a magnetostriction sensor, the voltage must be amplified 200 times (46 dB) [5]. On the other hand, the output voltage of a few V that is needed to control the microcontroller could be generated easily using a oscillator (function generator) and a variable capacitor [6,7]. The principal method of this study was the CR high-pass filter method, which we have used in previous studies [6,7]. The voltage output by a capacitor and a filter consisting of resistance relates to the capacitance of the variable condenser via the angle of rotation and changes therein. Greater capacitance leads to greater change in the voltage. In our former study, the greatest capacitance used a variable condenser of 80 pF. In this study, we have used a variable capacitor of 220 pF maximum, which is about four times greater than that in former study. In addition, the capacitor used in the former study was in contact with the Cu electrode plate via a Bakelite board. Its durability was high, as in this variable capacitor, the electrode plates did not touch each other. As for the potentiometer (variable resistance), the resistance body and a moving terminal were in contact, and the durability in relation to contact resistance and abrasion at the point of contact was a problem. It is thought that its durability was advantageous, as the plates in the variable capacitor were not in contact.

In this study, we fabricated a steering system using a variable capacitor and an Arduino UNO R3 microcontroller (Arduino Co., Ltd. [8]), which was installed with an ATMega16U2 Processor, an 8-bit AVR® RISC-based microcontroller, and a stepper motor. A variable capacitor was used for the rotation angle sensor. A resistor was combined with this variable capacitor, and together they constituted the high-pass filter with a CR circuit.

In this experiment, a microcontroller, a steppermotor used a ready-made commercial article. On the other hand, the rotation angle sensor was made with a handicraft except the IC of the oscillation element. The rotation angle sensor is comprised of a variable capacitor, various filters, a diode bridge, resistance, an inductor, a transistor for the signal amplifier. Students can understand the function of each part and the constitution of the circuit by making this sensor, and it is conceivable that a enginerring education effect is high.

By the experiment that this article presented, students can learn about the function of an electronic circuit and each element using capacitor, resistance, inductor, and diode. In addition, it is useful as engineering education as students can learn it about the basics and the usage for uses of microcontroller and the stepper motor.

II. MATERIALS AND METHODS

2.1 Steering system using a potentiometer, microcontroller, and stepper motor

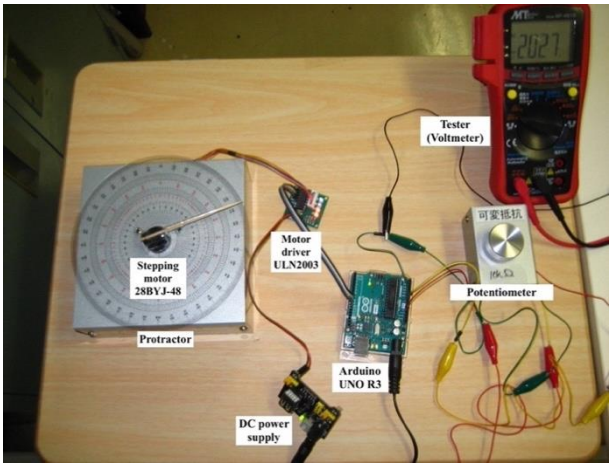


Figure 2-1. Photo of the steering system using a potentiometer, microcontroller, motor driver, and stepper motor.

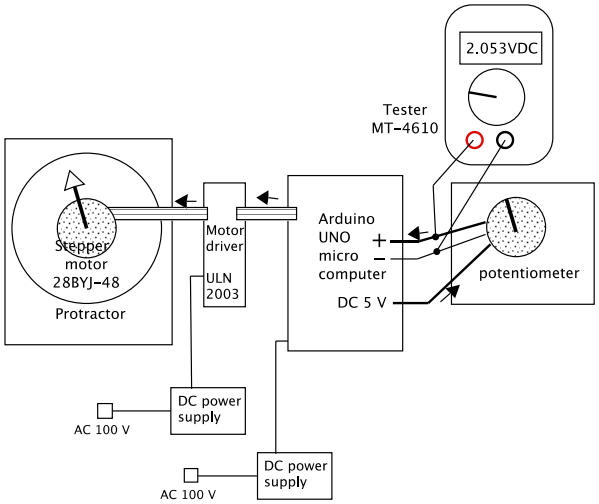


Figure 2-2. Schematic circuit diagram of the steering system using a potentiometer, microcontroller, and stepper motor.

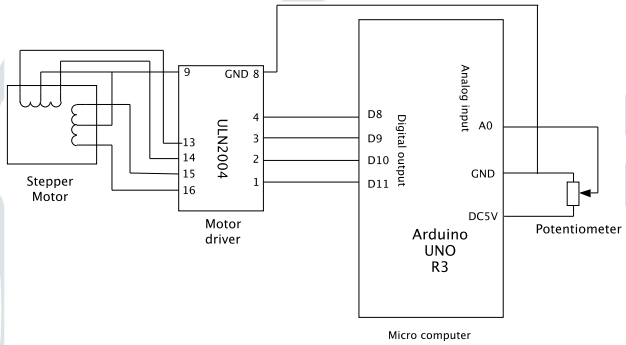


Figure 2-3. Schematic of the unipolar stepper motor driving system [25].

First, we fabricated a steering system using a 10 k Ω potentiometer (variable resistance, RV30-10kΩ), a microcontroller, and a stepper motor. Figure 2-1 shows the steering system comprising a potentiometer, microcontroller, and stepper motor.

Figure 2-2 is a schematic diagram of this system. Figure 2-3 shows the schematics of the unipolar motor driving system. Via the DC 5 V output terminal of the microcontroller (Arduino UNO R3), DC 5 V was applied to the 10 kΩ potentiometer. The positive electrode of the output point of the potentiometer was connected to the analogue signal input terminal A0 of the microcontroller, and the negative electrode was connected by the GND terminal of the microcontroller. The digital PWM output terminals (D8-D11) of the microcontroller were connected to the input terminals of the motor driver (ULN2003, Zafina Co., ltd.). A PWM signal was supplied by the microcontroller to the motor driver. In response to the PWM signal, the DC signal output by the motor driver was supplied to the stepper motor (28BYJ-48, Zafina Co., ltd.). This motor was of the PM (permanent magnet) type, and we used a unipolar motor. Plural slowdown gears were incorporated into the chassis of this motor, and the slow-down ratio was 1:64. The axle shaft of the last gear protruded out of the chassis of the motor and turned smoothly. This type of motor cycle usually has a low step resolution of 7.5 degrees and 48 steps per revolution (360 degrees) of the axle shaft of the stepper motor [20]. When adding the plural slowdown gears, the system undertook 48×64 = 3072 steps per revolution. The minimum angle of the axle shaft of the last gear for the first step was 360/3072 = 0.117 degrees.

The Arduino UNO program code for the control of motor driver is shown in Table 2-1 [25]. The device control library "Stepper.h" allowed the Arduino boards to control the stepper motor. This library allows users to control unipolar or bipolar stepper motors.

Table 2-1. Arduino UNO code as a program for the control of the ULN2003 motor driver, which was used in [25]. The comment for each lines explains the command for each line.

program code	comment
10 #include <Stepper.h>	Use Stepper.h library
20 #define STEPS 200	The step number of motors to use.
30 Stepper stepper (STEPS, 8, 10, 9, 11);	Appoint a pin number and generate the instance of the stepper class.
40 float val; 50 float previous = 0;	The last reading of the

60 void setup() {
70 stepper.setSpeed(90);
}
	analog input.
	
	Set rotation speed of the stepper motor as 90 RPM/s.

80 Void loop(){ 90 for (int i=0;i<100;i++){	Add the AD conversion 100 times.
100 val += analogReed(0); }	// Acquire a value of the potentiometer.
110 val = val/100; 120 stepper.step(val – previous);	Only the quantity that a value of the input voltage changed operates a motor.
130 previous = val; }	Leave the value of the sensor (potentiometer) voltage.

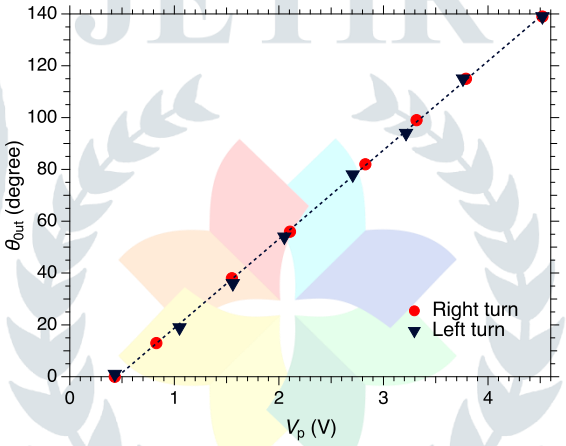


Figure 2-4. Output voltage of the potentiometer, V_p, vs. the rotation angle of the stepper motor, θ_{out}. Red circles and blue triangles indicate the output voltage of the right and left turning of the knob of the potentiometer, respectively. The dotted line is a linear fitting line.

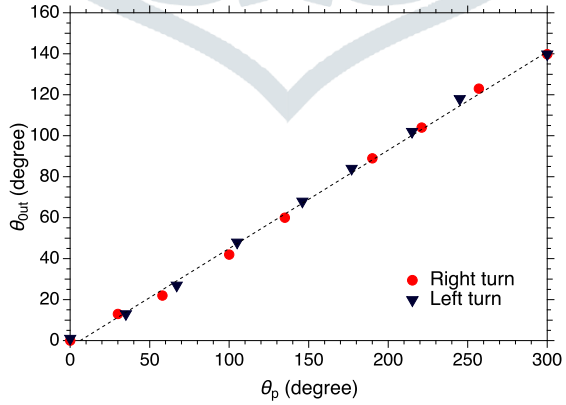


Figure 2-5. The rotation angle of the potentiometer, θ_p, vs. the rotation angle of the stepper motor, θ_{out}. Red circles and blue triangles indicate the output voltage of the right and left turning of the knob of the potentiometer, respectively. The dotted line is a linear fitting line.

Table 2-1 shows the Arduino UNO code used for the control of a ULN2003 motor driver. We added a line number to the beginning of each line for clarity. Please exclude these line numbers when using the code. In this program, we used the Stepper. h library (macro program included in the Arduino system), which was assigned at L10. This library enables the Arduino boards to control a variety of stepper motors, and allows the control of a unipolar or bipolar stepper motor [25]. In this study, we used a 28BYJ-48 unipolar stepper motor. Therefore, this library is suitable for use to control a motor. L30 denotes a command

appointing a pin number and generates the instance of the stepper class. L70 denotes the rotation speed of the stepper motor as 90 RPM/s. This rotation speed was chosen in reference to [16]. According to the results of this study, the best rotation speed for which the error of the turn was small was 90 RPM/s when using the Arduino atmega 2560 microcontroller. When the Arduino UNO R3 microcontroller we used was operated at over 100 RPM/s, the rotation angle became small. L100 denotes the value of the difference acquired in the output voltage of the potentiometer. L20 denotes a command according to which only a change in the value of the input voltage operates the motor. L130 denotes the command to leave the value of the output voltage of the potentiometer unchanged. When this program was operated, a PWM signal was transmitted to a motor driver via a microcontroller, commanding the turning of the stepper motor only at a time proportional to the amount of change in the output voltage of the potentiometer [25].

Figure 2-4 plots the output voltage of the potentiometer V_p vs. the rotation angle of the stepper motor. The resistance range of this potentiometer was from 1 kΩ to 10 kΩ. Therefore the output voltage of the potentiometer was not 0 V but 0.4 V, which was one-tenth of the maximum output voltage of the potentiometer. The value of θ_{out} was proportional to that of V_p, with an error of ±0.4%. This was a good proportion. The value of V_p was proportional to the resistance R_p between the positive pole and the negative pole of the potentiometer. R_p was proportional to the rotation angle of the knob of the potentiometer. Therefore, it was confirmed that the motor turned in proportion to the axial angle of rotation of the meter.

Figure 2-5 plots the rotation angle of the potentiometer θ_p vs. the rotation angle of the stepper motor, θ_{out}. The θ_{out} was proportional to the θ_p with an error of ±1.7%. Therefore, it was confirmed that the motor turned in proportion to the axial angle of rotation of the meter.

2.2 Steering system using a variable capacitor, microcontroller, and stepper motor

A steering system using a potentiometer and microcontroller is described in subsection 2.1. We have further investigated the mode of control of the angle of rotation of a motor using a variableness capacitor in place of a potentiometer. Figure 2-6 shows a circuit diagram of the steering system using a variable capacitor, microcontroller, and stepper motor. Figure 2-7 is a photo of this steering system. In this circuit, ① is an oscillatr and a CR high-pass filter consisting of an 8-223 pF variable capacitor (SY220, SANYO Co., Ltd.) with 200 kΩ resistance that was used as the rotation angle sensor.

Figure 2-8 shows a photo of LTC179, band-pass filter, and FET amplifier.

The oscillator was constructed by IC (LTC1799, Linear Technology Co., CA, USA) which incorporated an oscillation element and RLC band pass filter. LTC1799 is a precision oscillator which can produce a square wave [26].

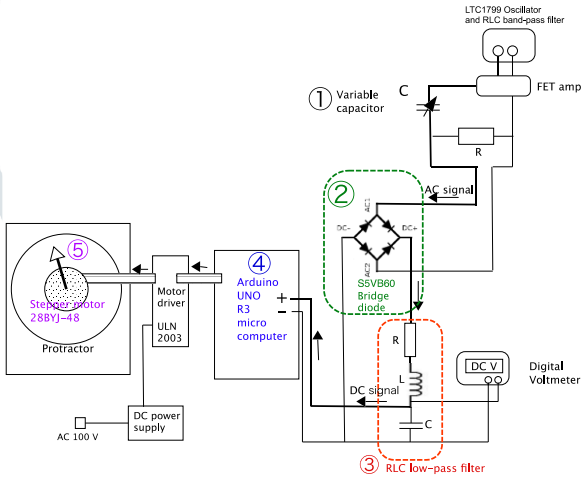
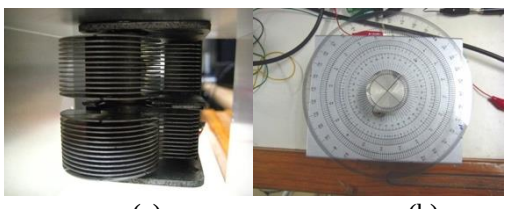
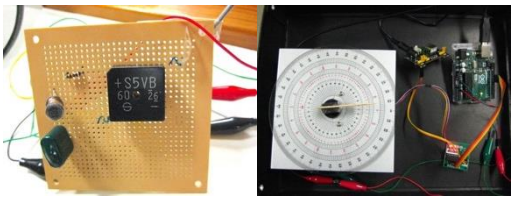


Figure 2-6. Circuit diagram of the steering system using a variable capacitor, microcontroller, and stepper motor.



(a) (b)



(c) (d)

Figure 2-7. Photo of the steering system, (a) variable capacitor, (b) knob of the variable capacitor and protractor, (c) bridge diode (S5VB), RLC low-pass filter, (d) microcontroller, motor driver, and stepper motor.

Figure 2-9 shows a schematic of LTC1799 and band-pass filter. LTC1799 is mainly composed of a master oscillator which which produces a square wave, and a programmable divider which can choose a frequency range. The oscillator frequency (f_{osc}) is programmed by a single external resistor (R_{SET}). The setting of f_{osc} was accomplished by Rset and R1 (3.3 kΩ) and the setting of the DIV (divider) terminal.

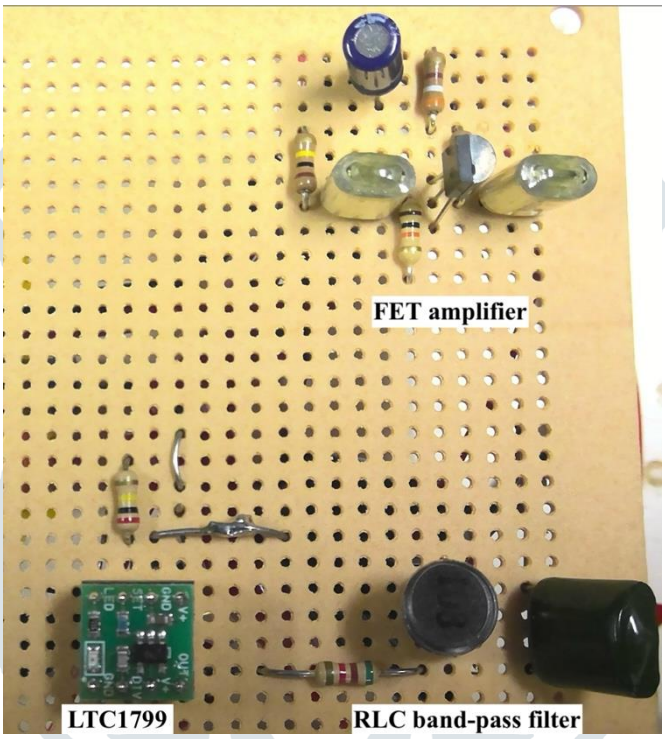


Figure 2-8. A picture of LTC1799, band-pass filter, and FET (2SK30A) amplifier.

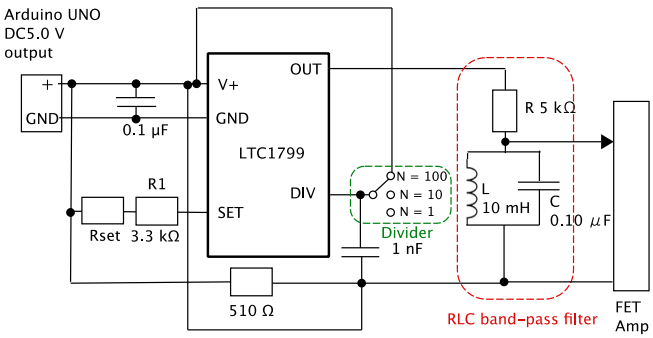


Figure 2-9. A schematic of LTC1799 and RLC band-pass filter.

The f_{osc} was calculated using the equation [26] :

$$f_{osc} = 10\ \text{MHz} \times \left(\frac{10\ \text{k}\Omega}{R_{set}+3.3\text{k}\Omega}\right) \times \left(\frac{1}{N}\right), \qquad (1)$$

where, N indicates a divider number. In this study, 5 kHz AC signal was used. For $f_{osc} < 100$ kHz, N = 100. As for $f_{osc} = 5.0$ kHz, the resistance of Rset was 200 kΩ.

Band-pass filter was composed of a resistor R = 5.0 kΩ, a inductor L = 10 mH, and a capacitor C = 0.10 μF. The impedance of the RLC band-pass filter was calculated by using the equation [27]:

$$\dot{Z} = R + \frac{1}{\frac{1}{iL\omega}+iC\omega} = \frac{R(1-LC\omega^2)+iL\omega}{1-LC\omega^2} \quad , \qquad (2)$$

where, $\omega^2$was defined as $\frac{1}{LC}$. When $\dot{Z}$ becomes maximum value, the denominator of equation (2) becomes zero. Therefore :

$$1 - LC\omega^2 = 1 - \frac{\omega^2}{{\omega_0}^2} = 0 \ , \therefore \ \omega = \omega_0 = \frac{1}{\sqrt{LC}} \qquad (3)$$

Therefore, $f_{\mathrm{osc}} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{0.01\times0.10\times10^{-6}}} = 5.0$ kHz.

Figure 2-10 shows the frequency dependemce of the transient voltage of the RLC band-pass filter. The oscillator frequency f_{osc} of this system was 4.92 kHz.

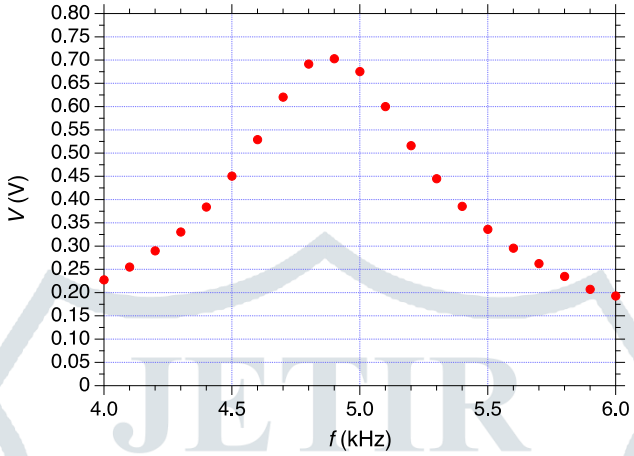


Figure 2-10. Frequency dependence of the effective value of output voltage of the RLC band-pass filter.

The frequencydependence of the output voltage of the RLC band-pass filter. Input signal was 3.0 Vpp AC sine wave, which was generated by a function generator (DF1906, NF Co., Ltd., Yokohama, Japan). The effective value of the output voltage of the RLC band-pass filter was detected by means of the digital mmultimeter (CD770, Sanwa Electric Instrument Co., Ltd., Tokyo, Japan). The peak frequency was 4.9 kHz, which was almost as same as the oscillator frequency f_{osc} of this system, 4.925 kHz.

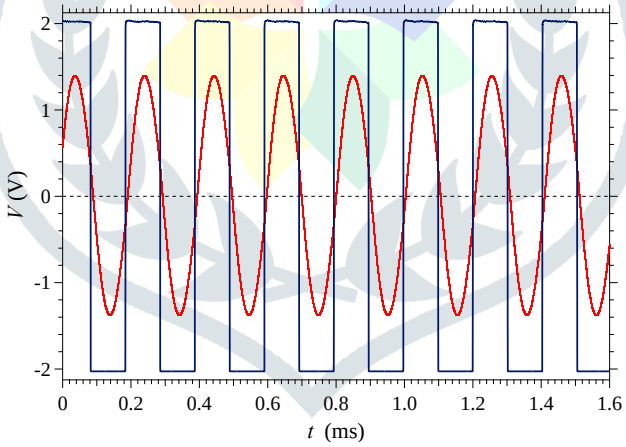


Figure 2-11. Time dependence of the output signal of LTC1799 oscillator (blue) and the output signal of RLC band-pass filter.

Figure 2-11 shows time dependence of the output signal of LTC1799 oscillator (blue) and the output signal of RLC band-pass filter. The peak to peak voltage of the output signal of LTC1799 oscillator and RLC band-pass filter was 4.06 Vand 2.73 V, respectively.

The output signal of RLC band-pass filter was amplified with an FET amplifier of the own work which we made before. The details of the FET amplifier are described in ref. [7].

A output signal of the FET amplifier was applied to the CR high-pass filter. The output voltage of the CR high-pass filter was changed with the rotation of the variable capacitor. The cut-off frequency f_0 can be calculated using the equation:

$$f_0 = \frac{1}{2\pi RC} \qquad (1)$$

In this CR high-pass filter, f_0 = 5 kHz at C = 150 pF and R = 200 kΩ. Therefore, it was expected that the output of the CR high-pass filter would change when knob of the variable capacitor was turned and the capacitance C was changed from 8 pF to 223 pF.

② Indicates a bridge diode (S5VB60). This element was installed to convert the AC output signal of the CR high-pass filter into a DC signal. Further, ③ shows an RLC low-pass filter used to remove ripple noise from the signal, with R = 9.1 Ω, L = 10.8 mH, and C = 47 μF. The frequency dependence of the magnitude of the attenuation was calculated via the transfer function defined in the following equation [28]:

$$\frac{V_o}{V_i} = \frac{\frac{1}{LC}}{s^2+\frac{R}{L}s+\frac{1}{LC}} \qquad (2)$$

where V_i and V_o indicate the input and output voltages of the RLC circuit. Figure 2-12 plots the frequency dependence of the magnitude of the attenuation. There was a drop in the signal at -50 dB to 5 kHz. The DC signal output from the RLC low-pass filter was directed into an analogue A0 terminal of the ④ Arduino UNO R3 microcontroller. The arrangement of this microcontroller, motor driver, and stepper motor was the same as that used in the experiment on the steering system using a potentiometer mentioned in subsection 2.1.

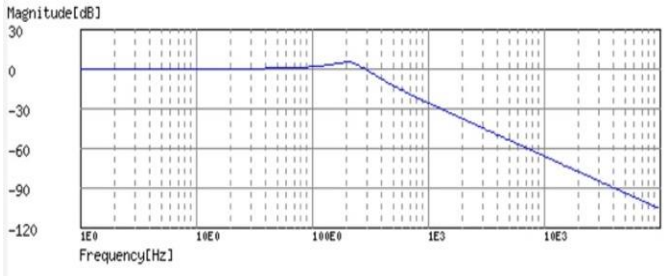
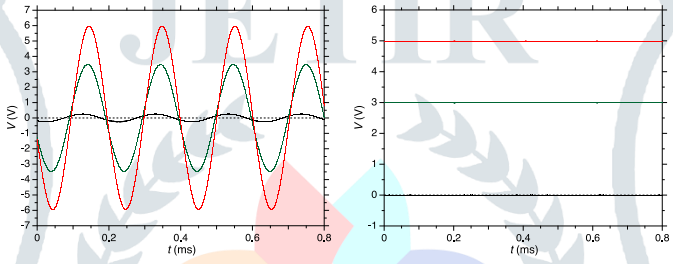


Figure 2-12. The frequency dependence of the magnitude of the attenuation, calculated using a web tool for the RLC circuit [23].



(a) (b)

Figure 2-13. (a) The time dependence of the output voltage of the CR high-pass filter for C = 220 pF. (b) The time dependence of the output voltage of the RLC low-pass filter.

Figure 2-13 (a) plots the output voltage of the CR high-pass filter for C = 220 pF, and (b) shows the output voltage of the RLC low-pass filter. A 5 kHz AC signal was converted into a clean DC voltage signal using a bridge diode and an RLC low-pass filter. This voltage of this DC signal was from 0 V to 5 V. As the maximum value of the input of the microcontroller was DC 5V, the performance of the microcontroller was fully exploited.

III. RESULTS AND DISCUSSIONS

3.1 Steering system using a variable capacitor, microcontroller, and stepper motor

We developed a steering system using a variable capacitor and an Arduino UNO R3 microcontroller. Figure 3-1 plots the angular dependence of the capacitance of the variable capacitor, where θ_{in} indicates the rotation angle of the variable capacitor, measured using a protractor. The approximate curve (fitting line) of Fig. 3-1, which was indicated by dotted line, used a sixth multinomial equation. The capacitance of the variable capacitor was measured using an RLC meter (LCR-916, TEXIO Co., Ltd.). Figure 3-2 plots the results calculated for the angular dependence of the capacitance in a V_{out}/V_{in} ratio. V_{in} and V_{out} indicate the input voltage and output voltage of the CR low-pass filter, respectively, as shown in Figure 3-2. The V_{out}/V_{in} ratio, indicated by the red line in Figure 3-1, was calculated via Equation (3):

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+\left(\frac{1}{2\pi RfC}\right)^2}} \qquad (3)$$

Figure 3-2 indicates that the V_{out}/V_{in} ratio was proportional to the rotation angle of the variable capacitor, which ranged 60-140 degrees. Therefore, for this variable capacitor, we can conceive that the V_{out}/V_{in} ratio was between 60 and 140 degrees.

Figure 3-3 plots the θ_{in} vs. V_{out}/V_{in} ratio. The error between the red line (calculated value) and the linear fitting line ranging 60-140 degrees, interms of the value of θ_{in}, was $\pm$0.3 %. In this range, it is expected that the rotation angle of the variable capacitor and the DC voltage output by the RLC circuit will be proportional. This has also been suggested experimentally, as the angle of

rotation of the capacitor and the angle of rotation of the stepper motor are proportional in the results derived for the potentiometer, as shown in Figure 2-4.

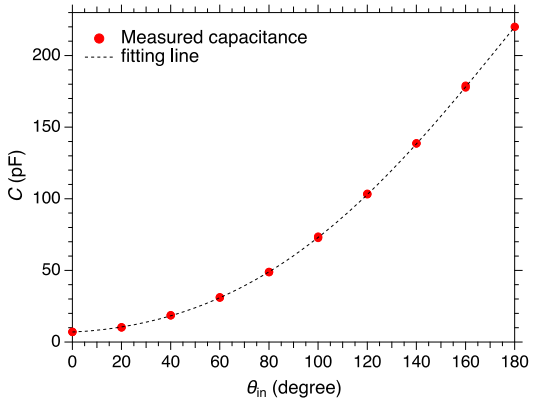


Figure 3-1. Angular dependence of the capacitance of the variable capacitor. The dotted line is the fitting line.

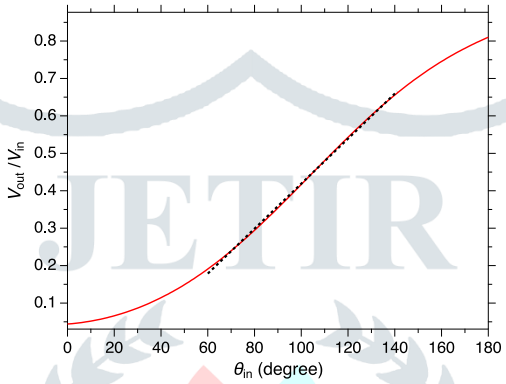


Figure 3-2. The red line shows the calculated result of the angular dependence of the capacitance for the V_{out}/V_{in} ratio. The dotted linear line shows the fitted linear line between 60 and 140 degrees.

Figure 3-3 and figure 3-4 plot the angular dependence of the voltage V_{DC} output by the RLC low-pass filter. The horizontal axis of Figure 3-3 indicates the rotation angle of the variable capacitor, θ_{in}, and the horizontal axis of figure 3-4 indicates the rotation angle of the stepper motor, θ_{out}. These two figures show proportional relations between the vaues of θ_{in} within 60-140 degrees.

Figure 3-5 plots the rotation angle of the variable capacitor, θ_{in}, vs. the rotation angle of the stepper motor, θ_{out}. Figure 3-6 shows the results for a value of θ_{in} between 60 and 140 degrees and of θ_{out} between 15 and 105 degrees. The value of θ_{out} was proportional to the value of θ_{in} in the range of $\pm$1.0% of error. As for the use of a potentiometer as a rotation angle sensor, the θ_{out} was proportional to the rotation angle of the potentiometer, θ_p, with an error of $\pm$1.7%. The error of the system using a variable capacitor was comparable to that of the system using a potentiometer.

The common wheel steering angle of a car is 40 degrees inward and 35 degrees outward [29]. The difference in the angles is 75 degrees. As shown in Figure 3-6, the roration angle range of the stepper motor θ_{out} was 88 degrees. Therefore, it is conceivable that the system developed in this study can be applied as a car steering system.

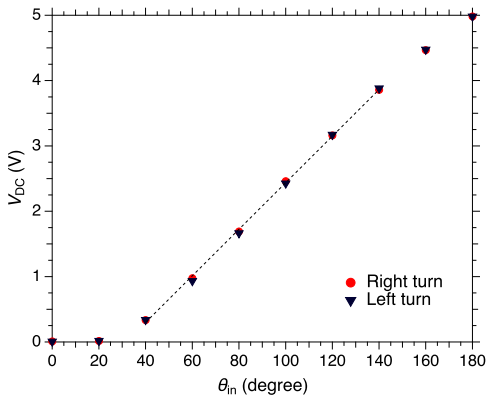


Figure 3-3. Angular dependence of the voltage V_{DC} output by the RLC low-pass filter. The horizontal axis indicates the rotation angle of the variable capacitor.

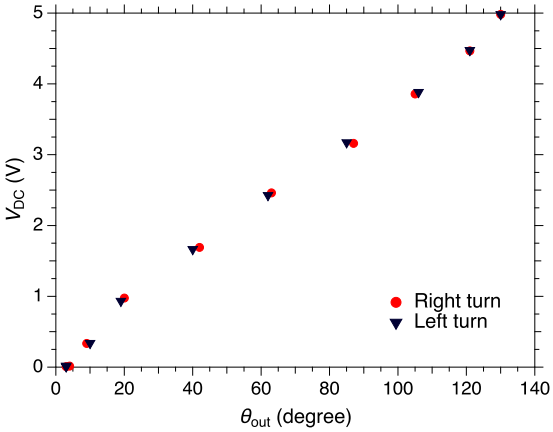


Figure 3-4. Angular dependence of the voltage V_{DC} output by the RLC low-pass filter. The horizontal axis indicates the rotation angle of the stepper motor.

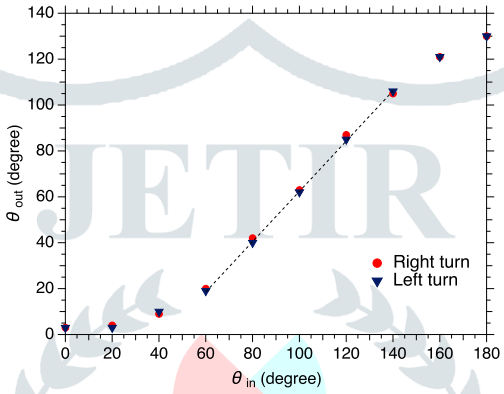


Figure 3-5. The rotation angle of the variable capacitor vs. the rotation angle of the stepper motor. The dotted line is the linear fitting line.

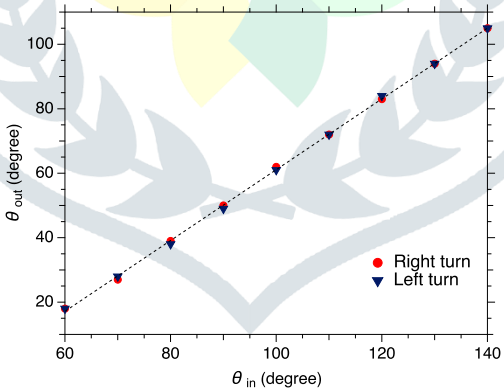


Figure 3-6. The rotation angle of the variable capacitor θ_{in} vs. the rotation angle of the stepper motor θ_{out} for θ_{in} = 60-140 degrees. The dotted line is the linear fitting line.

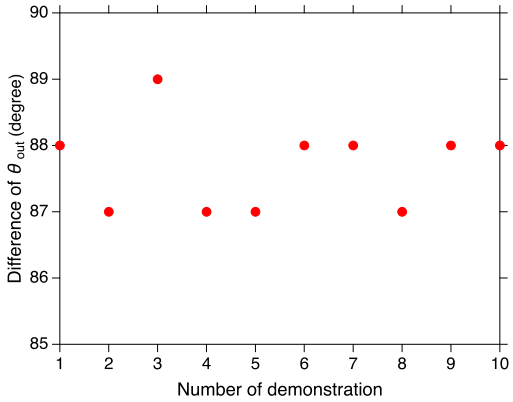


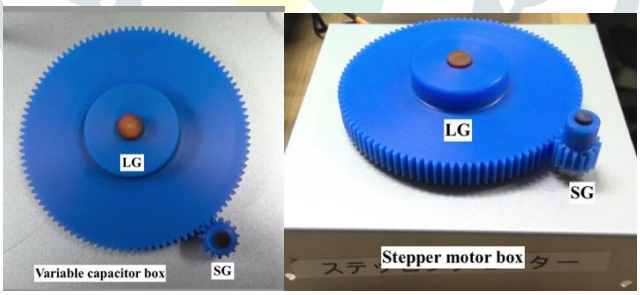
Figure 3-7. The difference in the roration angles of the stepper motor with 10 repetitions.

Figure 3-7 plots the difference in the roration angle of the stepper motor over 10 repetitions. The error of the difference in the rotation angle was ±1.6%. There was no change in the rotation angle of the stepper motor even with repetitions. When the steering system using this variable capacitor was used for the steering of a tire, an error arose that was caused by the diversion of the knuckle arm and the gear between the stepper motor that was moving the axle of the tire, but this was expected, as it correlates with an error encountered at the same level in the steering system using a potentiometer.

3.2 The rotation mechanism that combined with a reducing gear

As shown in Figure 3-7, the rotation angle range which was useful to use as rotation angle system was less than 90 degrees. For the purpose of increasing rotation angle, the rotation mechanism was created which was combined two gears. Figure 3-8. shows a variable capacitor gears, and a stepper motor gears. PS plastic gears were used. The size of the variable capacitor gears are of 100 mm in diameter and module 1(larger gear, abbreviation LG), and of 15 mm in diameter and module 1 (smaller gear, abbreviation SG) (KHK co., Ltd. Saitama, Japan). The gear ratio was 100:15. A bakelite cylindrical rod of 10mm in diameter to the axis of the variable capacitor and put it through the central axis of LG. The LG on the stepper motor was installed likewise, too. The SG was installed close to The LG. When the SG installed on a variable capacitor box was rotated, the LG which was connected to the variable capacitor was rotated. The LG of the stepper motor box turned in proportion to angle of rotation of the LG of the variable capacitor box. Finally, the SG installed on a variable capacitor box was rotated.

Figure 3-9 shows the rotation angle of the small gear angle of the variable capacitor, θ_{gin} vs. the rotation angle of the small gear angle of of the stepper motor, θ_{gout}. The capacity of variation of θ_{gin} and θ_{gout} was 533 degrees and 587 degrees, respectively. The wide-angle turn was realized by making plural gears.



(a) (b)

Figure 3-8. Pictures of (a) variable capacitor box, and (b) stepper motor box.

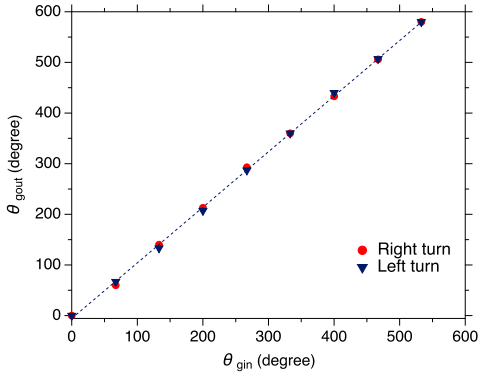


Figure 3-9. The rotation angle of the small gear angle of the variable capacitor, θ_{gin} vs. the rotation angle of the small gear angle of of the stepper motor, θ_{gout}.

3.3 Comparison with other capacitive rotation angle-sensing systems

Next, we can compare our system with other capacitive rotation angle-sensing systems. Table 3-1 shows the characteristics, rotation angle ranges, and accuracy of these systems. Li et al. developed a capacitivecircle range of measurement (360 degrees) [11]. The sensor is composed of three main parts: the capacitive sensing element, a signal processor and a microcontroller. The signal processor is composed of a capacitive-controlled oscillator, a frequency divider, a counter and a selector. The signal processor has a multi capacitance input and a single period-modulated output, and includes a nearly linear capacitance/period converter.

Table 3-1. The characteristics, rotation angle ranges, and accuracy of these systems.

Reference	Characteristic	Rotation angle range	Accuracy
This work	Steering system with Arduino microcontroller	88 degrees 587 degrees (combined with reduction gear)	±1.0%
Li 1996 [11]	Signal processor and a nearly linear capacitance/period converter	360 degrees	1.5 arcsec nonlinearity: less than 1.58 arcsec measurement time of 140 ms
Fu 2020 [12]	Sensor probe: differential multilayer ring structure using a CAV444 capacitor voltage conversion circuit and digital processing system	360 degrees	The nonlinear error is less than 4.89%; the hysteresis error is less than 3.72%
Qin 2018 [13]	Uses a capacitance convertor-integrated circuit CAV424 and a voltage–current convertor (AM402); the signal of the capacitive sensor is converted into a standard industrial current output ranging from 4 to 20 mA	90 degrees	Coefficient of determination R^2 = 0.9973
Flumek 2002 [14]	Contactless torque sensor for rotating shafts	±7.5 degrees	0.1 degrees

High-accuracy angle measurement was performed with error in the order of 1 arcsec = 1/3600 degree. Fu et al. developed a capacitance angle sensor using a concentric ring multi-layer differential [12].This sensor probe had a differential multilayer ring structure, which greatly increased the positive area of the microplate and effectively improved the range and measurement accuracy of the sensor. In addition, a capacitance convertor-integrated circuit CAV444, a voltage–current convertor AM402, and an AD conversion integrated chip ADS1115 were included in the signal processing circuit system, which together reduced the interference of parasitic capacitance, suppressed common mode interference, and improved measurement accuracy and sensitivity. The nonlinear error here was less than 4.89%. Qin developed a non-contact capacitive angle sensor with linear current output [13]. Through a capacitance convertor-integrated circuit CAV424 and a voltage–current convertor AM402, developed by AMG Co., Ltd. in Germany, the signal of the capacitive sensor was adapted to the standard industrial current output, ranging from 4 to 20 mA. This yielded a highly linear output current with a coefficient of determination, R^2, of 0.9973, within the sensor angle range of 0 to 90 degrees.

Flumek et al. developed a contactless torque sensor based on a capacitive angle and angular rate sensor, which was used for measuring the torque in mechanical systems [14]. The relative angle between the two rotors and the absolute position of the rotor blades were here calculated from measurements of the capacitive coupling between different transmitting stator segments and a single receiving electrode.

These sensors all use converter circuits and digital processing systems. On the contrary, the capacitive rotation angle-sensing system developed in this study was constructed using a CR filter with a variable capacitor, a bridge diode, and an RLC low-pass filter, and was able to acquire the voltage signal in proportion to the rotation angle. This simple system can obtain a rotation angle

with the precision of ±1.0% error. As the Arduino UNO microcontroller features a DC voltage input terminal, it is advantageous that a DC voltage of 0 to 5V is required to drive the stepper motor via microcontroller.

IV. Conclusion

In this study, we fabricated a steering system using a variable capacitor, a microcontroller (Arduino UNO R3), and a stepper motor for use of experimental system of experimental engineering in university class.

The rotation angle sensor was made with a handicraft except the IC of the oscillation element. The rotation angle sensor is comprised of a variable capacitor, various filters, a diode bridge, resistance, an inductor, a transistor for the signal amplifier. Students can understand the function of each part and the constitution of the circuit by making this sensor.

A variable capacitor of 220 pF maximum was used as the rotation angle sensor. This variableness capacitor was of the multi-disc type, and there was a gap between each disc. Therefore, we can assume its durability was high. A resistor was combined with this variable capacitor, and together, these constituted a high-pass filter with a CR circuit. The AC signal input into this circuit was changed by turning the knob of the variable capacitor. The output AC signal was changed to a DC signal varying from 0 V to 5 V, which is at the upper tolerance limit of the Arduino microcontroller, via a bridge diode and an RLC low-pass filter. The DC signal was input into an analogue terminal of the microcontroller, and the stepper motor connected to the microcontroller was rotated. The rotation angle of the stepper motor was proportional to the rotation angle of the variable capacitor within a standard deviation of ±1.0%. The most common wheel steering angle of a car is 40 degrees inward and 35 degrees outward. The difference between these angles is 75 degrees. As shown in Figure 3-6, the rotation angle range of the stepper motor θ_{out} was 88 degrees. When using a potentiometer as the rotation angle sensor, the θ_{out} was proportional to the rotation angle of the potentiometer, θ_p, with an error of ±1.7%. The error of the system using a variable capacitor was equal to that of the system using a potentiometer.

For the purpose of increasing rotation angle, the rotation mechanism was created which was combined two gears. The capacity of variation of θ_{gin} and θ_{gout} was 533 degrees and 587 degrees, respectively. The wide-angle turn was realized by making plural gears.

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