Operational Amplifiers in Discrete Time Control Systems: Influence of the Rail-to-Rail Feature on their Performance

ÁLVARO LLARÍA[1], JAIME JIMÉNEZ[2], UNAI BIDARTE[2], OCTAVIAN CUREA[1]
[1]Laboratoire en Ingénierie des Processus et des Services Industriels (LIPSI)
École Supérieure des Technologies Industrielles Avancées (ESTIA)
Technopôle Izarbel, 64210 Bidart
FRANCE
[2]Departamento de Electrónica y Telecomunicaciones
Universidad del País Vasco, Escuela Técnica Superior de Ingeniería
Alameda Urquijo, s/n, 48013 Bilbao
ESPAÑA
a.llaria@estia.fr, jaime.jimenez@ehu.es, unai.bidarte@ehu.es, o.curea@estia.fr

Abstract: - One of the usual features that an operational amplifier may offer is the *rail-to-rail* capability. This means that its output range is equal to the power voltages (positive and negative or zero) without any offset. In some cases this feature does not concern with the performance of the system because it does not operate in the limits of the output range or the offsets are small enough not to care about them. Nevertheless, when an accurate instrumentation system must be used, as in this article, the *rail-to-rail* capability is crucial not to degrade the performance. For instance, the circuit may loose linearity and resolution if the operational amplifiers are not adequate. In our case, a circuit to perform some discrete time control algorithms needed a maximum output range for the system to work properly. With the initial operational amplifiers, the performance was not adequate. After setting *rail-to-rail* ones the problem has been resolved.

Key-Words: - Operational amplifier, rail-to-rail, output range, linearity, RST discrete time controller.

1 Introduction

A Discrete Time Control experimental setup has been developed in the *École Supérieure des Technologies Industrielles Avancées* (ESTIA) in collaboration with the enterprise *ALECOP*. By means of it, it is possible to make plenty of experiments in a physical workbench which seems a real system.

This module, which implements a RST controller [1], and allows observing the behaviour of some real thermal, hydraulic and mechatronic processes, has two main hardware parts: a microcontroller card and a signal shaping card. In addition, the module communicates with a PC in order to be programmed. The signal shaping card has several operational amplifiers, and other integrated circuits.

Among the most important features of an operational amplifier (symmetry of the power voltages, offset, CMMR, gain, input impedance, output impedance, frequency response, polarization currents, etc.) the *rail-to-rail* capacity sometimes is not taken into enough consideration [2]. But in our system, it has been crucial, so much that its correct operation has been disturbed. In next sections, the developed system will be described, as well as the solution adopted to avoid the problems originated in the operational amplifiers *rail-to-rail* feature.

2 Description of the System

The discrete time control system developed and constructed in ESTIA is described in this section, under two points of view: software and hardware. First of all, a brief description of the program that implements the RST controller is made, to finish with a wide depiction of all the electronic circuits.

2.1 Description of the Program

This section presents a functional description of the program which implements the RST algorithm. This program is implemented on a MC9S12E128 microcontroller, described in section 2.2.4.

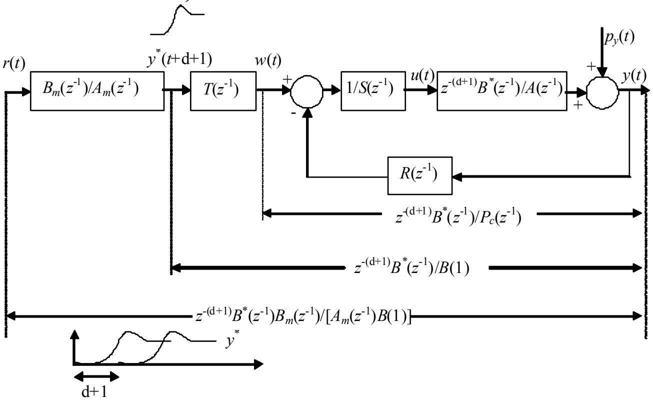

Fig. 1. Digital RST closed loop control structure.

Sensor and *set point* signals, after a scaling and filtering stage, go to the microcontroller's Analog to Digital Converter (ADC), in order to obtain *r* and *y* sampled signals (Fig. 1). These signals and the command signal *u* are needed to implement the difference equation which defines the RST controller.
At this point, the use of a Real Time Interrupt (RTI) is necessary. It is generated by an internal timer and used by the microcontroller to fix the sampling time. This is crucial to ensure a correct operation, because the Discrete Time Control must pick up samples with a fixed period.
The procedures performed by the microcontroller for each sample time are:
- start the AD conversions for *r* and *y* signals, pick up the results and store the values in temporary memory locations;
- shift the previous *r* values and put the new value in the attached vector;
- compute *y** using the reference model;
- shift the previous *y** and *y* values and put the new values in the attached vectors (*y**, *y* and *u* vectors are used by the difference equation);
- compute the difference equation to obtain the *u* current value;
- shift the previous *u* values and put the new value in the attached vector;
- the *u* current value becomes the input of the Digital to Analog Converter of the microcontroller (DAC), to deliver the analog signal to the rest of the circuit, where it will be scaled.
The DA and AD converters and the RTI configurations are made in the program initialization sequence.

2.2 Description of the Electronic System

In terms of hardware subsystems, the entire module consists of two parts: the (signal shaping) electronic card and the LVCS12 module which contains a Motorola MC9S12E128 microcontroller. The basic interactions between each element of this new module are described in Fig. 2.

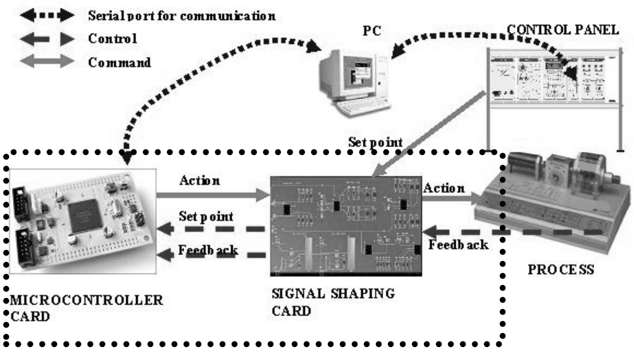

Fig 2. Physical parts of the complete system.

Inside the dotted rectangle are the blocks that compound the module made in ESTIA: the microcontroller card and the signal shaping card which are described in next sections.
The circuit, named Electronic Card in Fig. 3, makes three tasks: to give the power values employed by other modules (Power block in Fig. 3), to filter the electrical signals (Filtering block in Fig. 3), and to scale the signals between the correct values (Signal shaping blocks in Fig. 3).

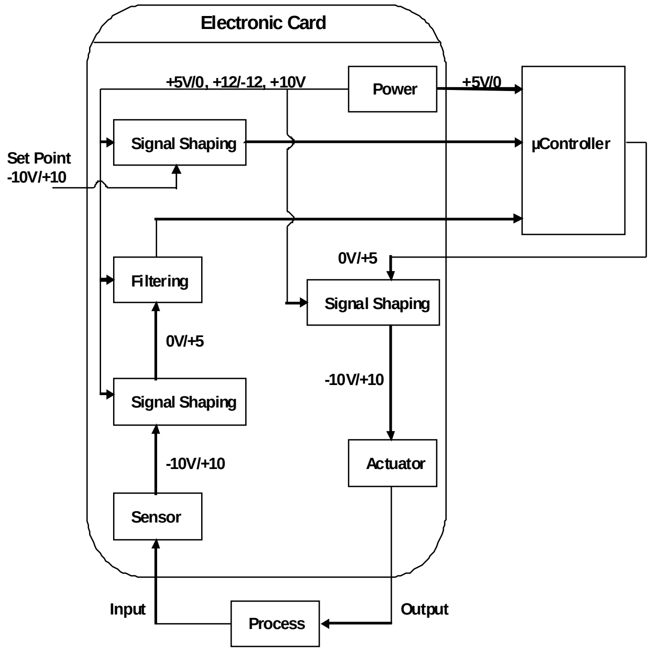

Fig. 3. Block diagram of the electronic system.

The *power block* adapts the power supplied to the microcontroller and the operational amplifiers, providing specific voltages. The operational amplifiers supplying power is -12 / +12V which is given by voltage regulators. The supply voltage for the microcontroller (+5V) is given by a voltage regulator too. A 5V voltage given by a precision voltage reference is amplified to obtain the desired 10V reference.
The *filtering block* is an anti-aliasing filter used before the signal sampler to restrict the bandwidth of the signal to approximately satisfy the Shannon sampling theorem. It is necessary to filter separately the three existing process (hydraulic, thermal and mechatronic), because of the different dynamics of each one. The dynamics of the process is directly related with the filter cut-off frequency. The three filters are hardware implemented and their outputs are connected to three analog inputs of the microcontroller. The analog input (therefore the filter) and the associated sampling time are selected in the program according to the desired dynamics.

Signal shaping blocks are used in order to scale the microcontroller signals (0V, +5V) into the levels of the electronic card (-10V, +10V), and vice – versa. To make this, it is necessary to use a voltage reference which must be very accurate. This voltage reference is provided by the circuit REF 195 GP of *Analog Devices*, which gives an output of 5 Volts [3]. This 5V reference is employed to obtain a new reference of 10V by using a non inverting amplifier.

2.2.1 The Power Block

There are three voltages needed among those which are not given by the existing bench: the +5V/0V, +12/-12V and the +10V. The circuits which supply those voltages are described next.

+10V Supplying Circuit

This circuit is based on a component named REF195. This is a precision micro power component which can be used as reference voltage. It accepts as input a voltage in the range -0.3V/+18V. In this application, the REF195 is supplied by a +12V tension given by a circuit described further. This 5V voltage is then used as input of an amplifier in order to obtain a 10V voltage with a good precision to be used by the *Signal shaping blocks*.

The schematic is depicted in Fig. 4.

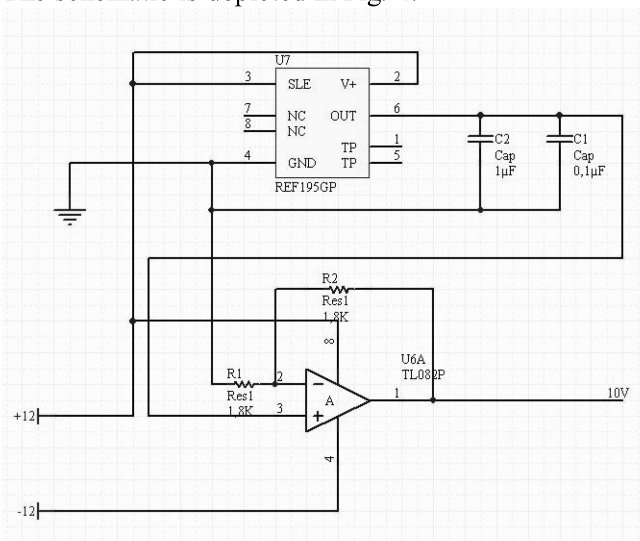

Fig. 4. +10V supplying circuit.

+12/-12V and +5V/0 Supplies

The +12V and -12V voltages are used in order to supply the operational amplifiers and the reference REF195. The +5V voltage is used as a power supply for the microcontroller. The circuits are equivalents in their principle. They are all based on voltage regulator. The +5V voltage regulator is not from the same family as the ±12V because it should be able to provide enough current. Circuits' configuration is shown in Fig. 5.

2.2.2 The Filtering Block

As it has been said before, this block is composed by three parts, one for each process.

Hydraulic Process Filter

In general, hydraulic processes have slow dynamics, so the frequencies which must be removed are the high ones. Hence, the solution chosen is a second order Butterworth low–pass filter. The characteristics of this filter are a cut-off frequency of 4Hz and a slope of -40dB by decade. It is possible to see its circuit in Fig. 6.

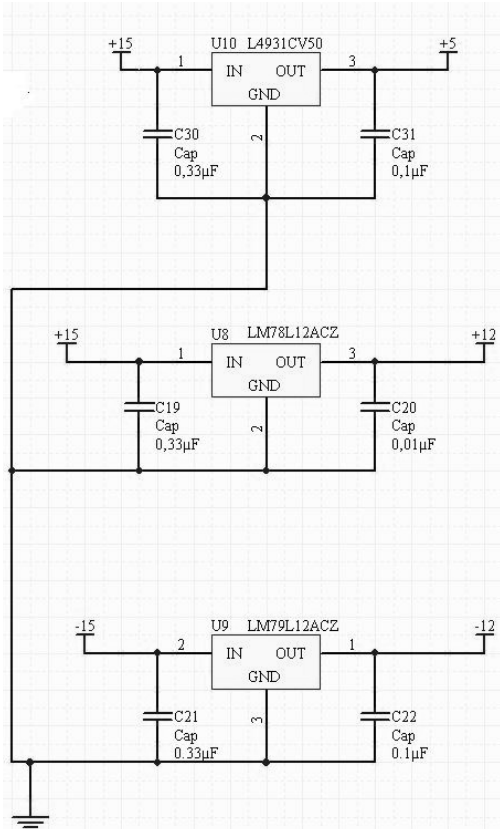

Fig. 5. +12/-12V and +5V/0 supplies schema.

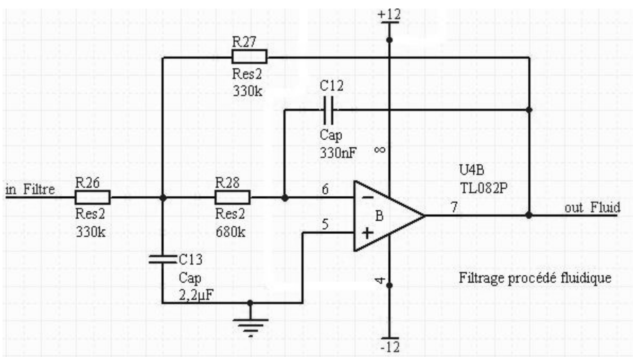

Fig. 6. Hydraulic process filter.

Thermal Process Filter

Thermal processes have also slow dynamics, lower than hydraulic ones. Again, the filter designed is a second order Butterworth low-pass filter to eliminate high frequencies. The features of the filter are a cut-off frequency of 1Hz and a slope of -40dB by decade. The scheme can be seen in Fig. 7.

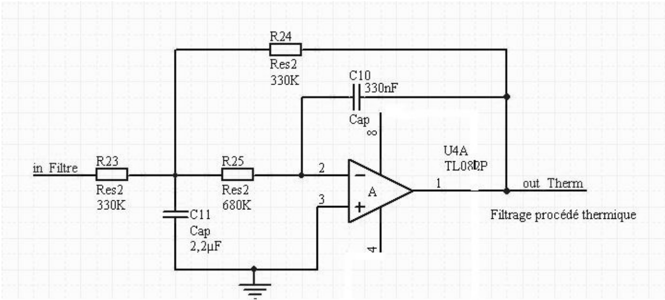

Fig. 7. Thermal process filter.

Mechatronic Process Filter

Here, operation and noise frequencies have values quite similar, so the filter must be very selective. To achieve that, the designed filter has fourth order. It was needed a response time of 10ms, which gives a frequency of 100Hz. Finally, it was chosen a cut-off frequency of 1kHz. The other characteristic of this filter is a slope of -80dB by decade. Fig. 9 shows the designed circuit.

It is important to say that hydraulic and thermal filters have got an inverted output. The solution to this problem has been to invert the input signal of those two filters with a simple inverter circuit with an operational amplifier. This is not a problem for the mechatronic filter because there are two stages, obtaining a non inverted output.

2.2.3 The Signal Shaping Block

There are several electrical signals which are inputs or outputs of the microcontroller, so, their voltage levels must be rescaled, according with the maximum values accepted by it.

As only one of the three processes will be used and the voltage range for the three processes is the same, it is enough to design one output signal (from the microcontroller) shaping card. Concerning the input signal (to the microcontroller), there are two signals: one for the *set point* and another one for the *feedback*. Hence, it is necessary to design two input signals shaping cards, but as there are the same range for these two input signals, it only must be made twice the same card.

Input Signals Shaping Cards

Here, the arriving signal is in a -10/+10V range and has to be rescaled into a 0/+5V range. The algorithm to make that operation is shown in Fig. 8.

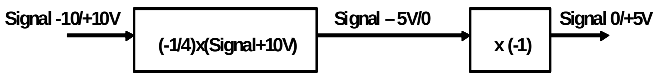

Fig. 8. Pass from -10/+10V to 0/+5V.

The circuit designed is a combination of an adder inverter stage with an inverter, and it is depicted in Fig. 11. The equation for the first amplifying stage is:

$$V_s = \frac{-(V_e + 10)\cdot R_9}{R_7 + R_9} = \frac{-(V_e + 10)}{4} \quad (1)$$

The equation for the second stage is:

$$V_s = -\frac{(V_e + 10)\cdot R_6}{R_5} = -V_e \quad (2)$$

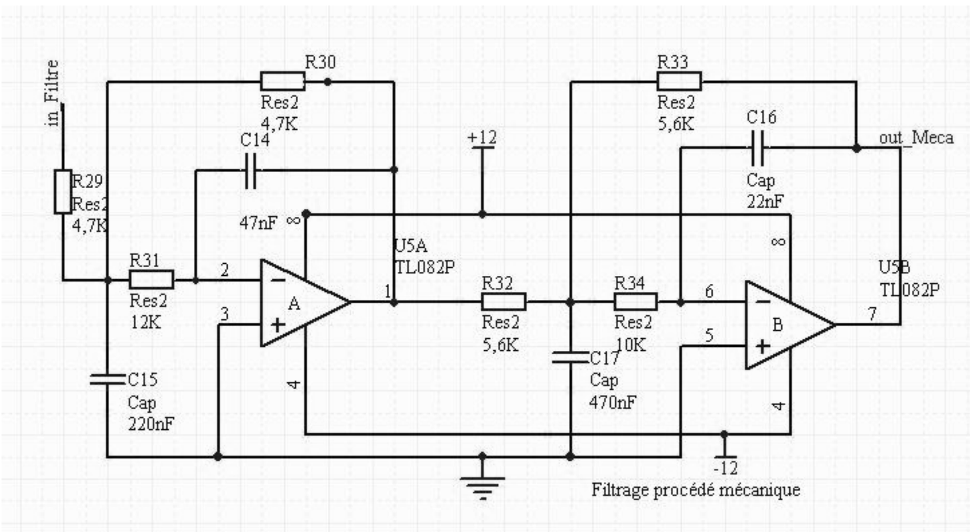

Fig. 9. Mechatronic process filter.

Finally, by combination of equations (1) and (2) it is had:

$$V_s = -\left(\frac{(V_e + 10)\cdot R_9}{R_7 + R_9}\right)\cdot\frac{R_6}{R_5} = \frac{V_e + 10}{4} \qquad (3)$$

These equations have been employed to fix the resistors values.

Output Signals Shaping Cards

Here, there is the inverse of the problem solved before: now the 0/+5V signal must be rescaled into a -10/+10V range. In Fig. 10 there is the algorithm chosen.

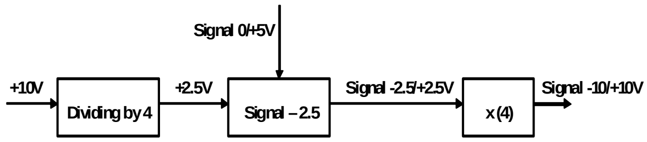

Fig. 10. Algorithm to pass from 0/+5V to -10/+10V.

The solution adopted is to use in cascade a voltage divider bridge, a two-input subtracter and a non-inverter amplifier with a gain value of 4. The schematic of the circuit is in Fig. 12.

Concerning the *voltage divider bridge* characteristics, the equations are:

$$V_s = V_e \frac{R_{22}}{R_{22} + R_{15}} \qquad (4)$$

So, the desired relationship is:

$$\frac{R_{22}}{R_{22} + R_{15}} = \frac{1}{4} \qquad (5)$$

That gives

$$V_s = V_e \frac{1}{4} \qquad (6)$$

$$R_{22} = R_{15}\frac{1}{3} \qquad (7)$$

The two-input *subtracter* equations are:

$$V_s = (Signal\frac{R_{18}}{R_{17}} - 2.5\frac{R_{19}}{R_{16}}) \qquad (8)$$

So, in the case that $R_{19} = R_{18} = R_{16} = R_{17}$, the final relationship is:

$$V_s = (Signal - 2.5) \qquad (9)$$

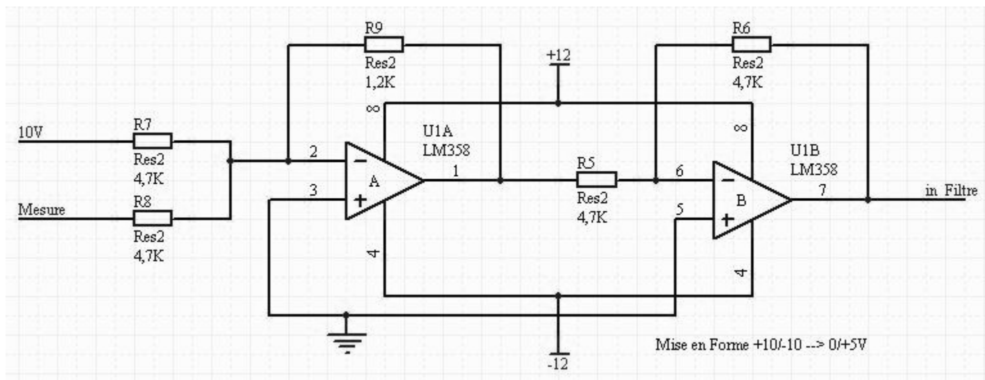

Fig. 11. Circuit employed to pass from +10/-10V to +5/0V.

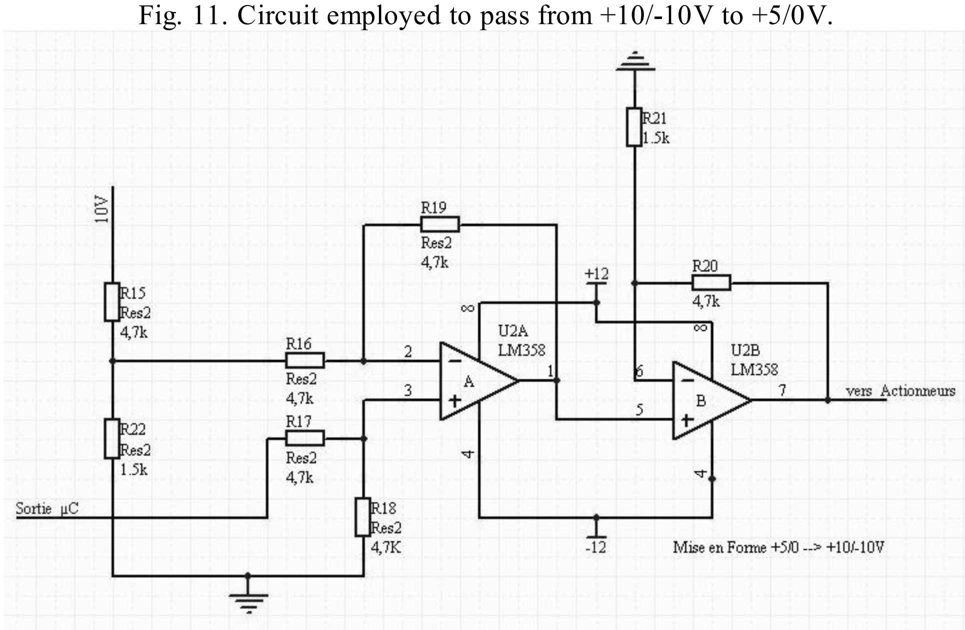

Fig. 12. Circuit employed to pass from +5/0V to +10/-10V.

Thirdly, the *non inverting amplifier* equations are:

$$V_s = V_e \frac{R_{21} + R_{20}}{R_{21}} \quad (10)$$

The needed gain is 4, so

$$\frac{R_{21} + R_{20}}{R_{21}} = 4 \quad (11)$$

$$3R_{21} = R_{20} \quad (12)$$

Finally, with the relationship of (12) it is verified that $V_s = 4V_e$, and the final equation is:

$$V_s = \left(Signal - \left(10 \times \frac{1}{4} \right) \right) \times 4 \quad (13)$$

Again, it is possible to see that the final values chosen for the resistors to implement the circuit (Fig. 11, Fig. 12) are not exactly the same calculated before. That is because of the selection of normalized values, in this case, the series E24.

2.2.4 The LVCS12 Module

LVCS12 is an easy applicable, credit card-sized Controller Module, based on the 16-bit HCS12 microcontroller family from *Motorola*. Fig. 13 shows this module.

The LVCS12 has a 16 MHz crystal clock and it is equipped with a powerful MC9S12E128 microcontroller unit (MCU). The microcontroller contains a 16-bit HCS12 CPU, 128 KB of Flash memory, 8 KB of RAM and a large amount of peripheral function blocks, such as SCI (3x), SPI, IIC, Timer, PWM, 10 bit ADC, 8 bit DAC and General-Purpose-I/Os. The MC9S12E128 has full 16-bit data paths throughout. An integrated PLL-circuit allows adjusting performance vs. current consumption according to the needs of the user application.

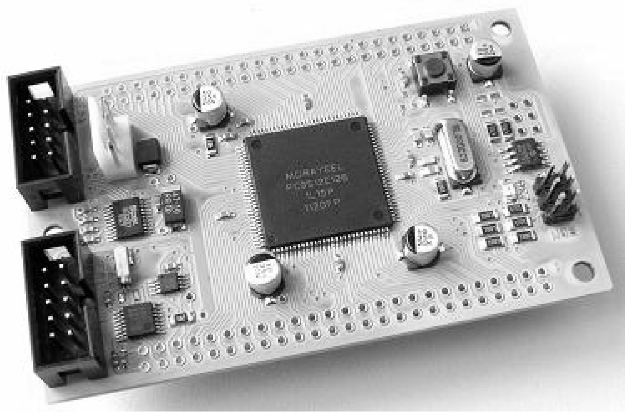

Fig. 13. LVCS12 module.

The LVCS12 module is also equipped with output amplifiers for the DAC channels and RS 232 transceivers for two serial interfaces (e.g. for PC connection) [4]. Students of ESTIA make practical works with LVCS12 module in Second Year in micro-programmed systems course, so it is easy for them to use it.

3 Characteristics and Parameters of Operational Amplifiers

One of the most important devices employed in this project are the operational amplifiers. In addition, the main problems found in the system's performance have been closely related with a parameter of these amplifiers. The characteristics of an ideal operational amplifier are described first, and the characteristics and performance limitations of a practical operational amplifier are commented next [5].

3.1 Properties of an Ideal Operational Amplifier

The operational amplifier (*opamp* abbreviated), is the most important linear IC. The circuit symbol of an *opamp* is shown in Fig. 14. The three terminals are: the non-inverting input terminal (V_+), the inverting input terminal (V_-) and the output terminal (V_o). The details of power supply are not shown in the circuit symbol.

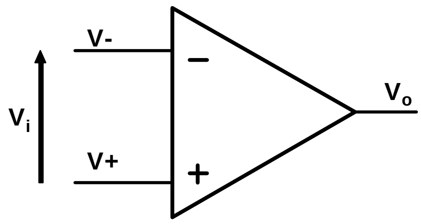

Fig. 14. Circuit symbol for an operational amplifier.

The basic equation which makes the relationship between output V_o and input V_i is:

$$V_o = -A_O V_i = -A_O (V_- - V_+) \quad (14)$$

Where A_o is known as the *open loop gain* of the *opamp*.

3.1.1 Infinite Open Loop Gain

From (14), it is found that $V_o = -A_O V_i$. Let V_o be - 10Volts, and A_o be 10^5. Then V_i is 100µV. Here the input voltage is very small compared to the output voltage. If A_o is very large, V_i is negligibly small for a finite V_o. For the ideal *opamp*, A_o is taken to be infinite in value. That means, for an ideal *opamp* $V_i = 0$ for a finite V_o. Typical values of A_o range from 20,000 in low-grade consumer audio-range *opamp*s to more than 2,000,000 in premium grade *opamps* (typically 200,000 to 300,000).

3.1.2 Infinite Input Impedance and Zero Output Impedance

An ideal *opamp* has infinite input impedance and zero output impedance. The sketch in Fig. 15 is employed to illustrate these properties. From Fig. 15, it can be seen that i_{in} is zero if R_{in} is equal to infinity.

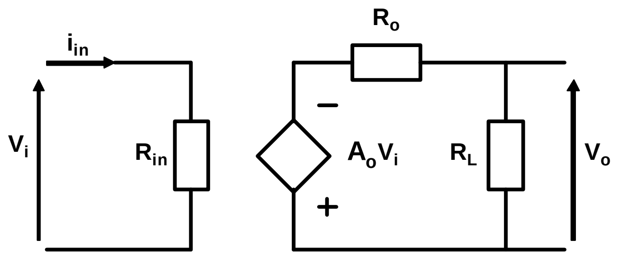

Fig. 15. Model of an operational amplifier (R_L is not part of the *opamp* model).

The second property of an ideal *opamp*: $R_{in} = \infty$ or $i_{in} = 0$.

From Fig. 15 it can be obtained:

$$V_o = -A_O V_i \times R_L / (R_o + R_L) \quad (15)$$

If the output resistance R_o is very small, there is no drop in output voltage due to the output resistance of an *opamp*.

The third property of an ideal *opamp*: $R_o = 0$.

3.1.3 Infinite Bandwidth

An ideal *opamp* has an infinite bandwidth, which means that its gain is constant for all the frequencies. A practical *opamp* has a limited bandwidth, which falls far short of the ideal value.

3.1.4 Zero Noise Contribution and Zero Output Offset

A practical *opamp* generates noise signals, like any other device, whereas an ideal *opamp* produces no noise. Premium *opamps* are available which contribute very low noise to the rest of circuits. These devices are usually called as premium low noise types.

The output offset voltage of any amplifier is the output voltage that exists when it should be zero. In an ideal *opamp*, this offset voltage is zero.

3.2 Real Operational Amplifier Parameters

A real operational amplifier has limitations to its performance. It is necessary to understand these limitations in order to select the correct *opamp* for an application and design the circuit properly.

Understanding operational amplifier circuits requires knowledge of the parameters given in specification sheets. The list below represents the most commonly needed parameters.

Open-Loop Voltage Gain. Voltage gain is defined as the ratio of output voltage to an input signal voltage, as shown in Fig. 14. The voltage gain is a dimensionless quantity.

Large Signal Voltage Gain. This is the ratio of the maximum allowable output voltage swing (usually one to several volts less than V_- and V_+) to the input signal required to produce a swing fixed by standards (normally, ±10 volts).

Slew Rate. The slew rate is the maximum rate at which the output voltage of an *opamp* can change and is measured in terms of voltage change per unit of time. It varies from 0.5 V/µs to 35 V/µs. Slew rate is usually measured in the unity gain non inverting amplifier configuration.

Common Mode Rejection Ratio (CMRR). A common mode voltage is one that is presented simultaneously to both inverting and non inverting inputs. In an ideal *opamp*, the output signal due to the common mode input voltage is zero, but it is nonzero in a practical device. The CMRR is the measure of the device's ability to reject common mode signals, and is expressed as the ratio of the differential gain to the common mode gain. The CMRR is usually expressed in decibels, with common devices having ratings between 60 dB and 120 dB. The higher the CMRR is, the better the device is deemed to be.

Input Offset Voltage. The DC voltage that must be applied at the input terminal to force the quiescent DC output voltage to zero or other level, if specified, given that the input signal voltage is zero. The output of an ideal *opamp* is zero when there is no input signal applied to it.

Power-Supply Rejection Ratio (PSRR). The power-supply rejection ratio is the ratio of the change in input offset voltage to the corresponding change in one power-supply, with all remaining power voltages held constant. The PSRR is also called "power supply insensitivity". Typical values are in µV/V or mV/V.

Input Bias Current. This is the average of the currents into the two input terminals with the output at zero volts.

Input Offset Current. The difference between the currents into the two input terminals with the output held at zero.

Differential Input Impedance. It is the resistance between the inverting and the non inverting inputs. This value is typically very high: 1MΩ in low-cost bipolar *opamps* and over 10^{12}Ohms in premium BiMOS devices.

Common-Mode Input Impedance. The impedance between the ground and the input terminals, with the input terminals tied together. This is a large value, of the order of several tens of MΩ or more.
Output Impedance. The output resistance is typically less than 100 Ohms.
Average Temperature Coefficient of Input Offset Current. The ratio of the change in input offset current to the change in free-air or ambient temperature. This is an average value for the specified range.
Average Temperature Coefficient of Input Offset Voltage. The ratio of the change in input offset voltage to the change in free-air or ambient temperature. This is an average value for the specified range.
Output Offset Voltage. The output offset voltage is the voltage at the output terminal with respect to ground when both the input terminals are grounded.
Output Short-Circuit Current. That is the current that flows in the output terminal when the output load resistance external to the amplifier is zero ohms (a short circuit to the common terminal).
Channel Separation. This parameter is used on multiple *opamp* ICs (device in which two or more *opamps* sharing the same package with common supply terminals). The separation specification describes part of the isolation between the *opamps* inside the same package. It is measured in decibels.
Rail-to-Rail Feature. This is the ability of an *opamp* to give at the output the maximum voltage values, limited of course by the supplying voltage. *Rail-to-rail* characteristic is well explained later in section 4.2 because of the importance of its effects over the system designed.

4 Problems Found in the Performance of the System

In this section, there is a description of the nature of the problems found in the system, which originated an incorrect operation of it.

4.1 Constraints in the Output Range of the Operational Amplifiers

At the beginning, we used the LM 358 operational amplifiers, which did not have the *rail-to-rail* feature [6]. When testing the system while running in normal conditions, it was not able to reach the expected maximum and minimum values of operation ranges. Wondering about the reason of this problem, most of the significant output voltages were measured and the data showed that the amplifiers could not give more than the power voltage, V_{CC}, minus a positive value, *b*, of some milivolts. When trying to give the *GND* voltage, the same matter appeared, it was not possible to reduce from a positive value of *a*, similar to *b* (Fig. 16).

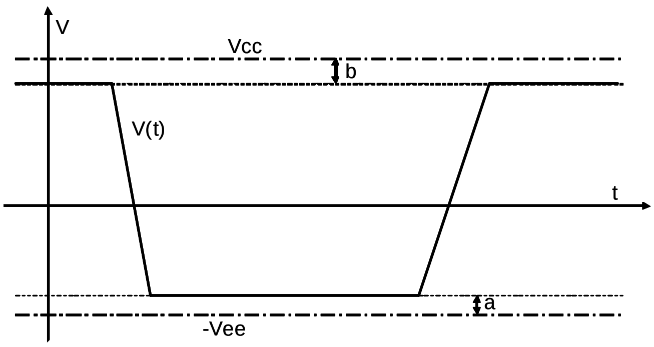

Fig. 16. Usual output range in an operational amplifier.

4.2 The Rail-to-Rail Feature

A simple operational amplifier cannot usually reach at the output its theoretical maximum and minimum values, i.e. V_{CC} and $-V_{ee}$ when powered symmetrically and V_{CC} and ground when asymmetrically [7].

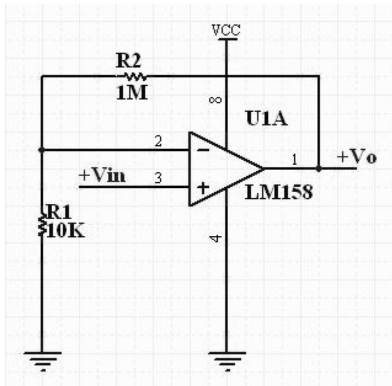

Fig. 17. Non inverting amplifier with asymmetrical power supply.

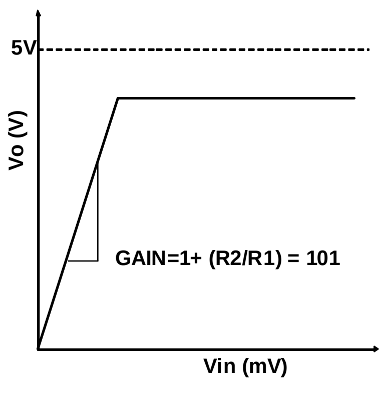

Fig. 18. Output characteristic of amplifier in Fig. 17.

Fig. 17 and Fig. 18 show this feature: an operational amplifier working in a non inverting configuration. In this case, the power supplying is asymmetrical with values 5V, 0V, and it is possible to see that the output voltage V_o can not reach the value of V_{CC} (5V). The operational amplifier is the LM 158, of the same family as LM 358.
The reason of this limitation can be explained by looking at the output stage of conventional amplifiers (Fig. 19). Most of the times this stage includes a transistor (BJT or MOSFET) with a serial resistor at the collector or drain.

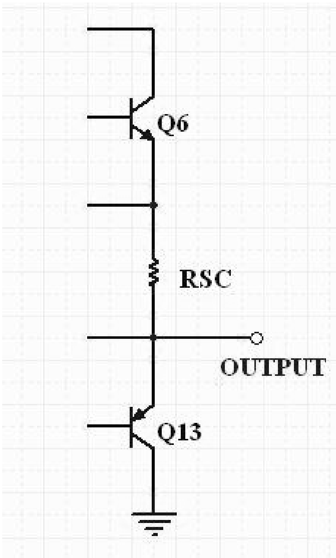

Fig. 19. Output stage of LM 358 operational amplifier.

So, although the transistor voltage dropout may be insignificant, if the output current has a usual value, the voltage dropped in the resistor must be taken into consideration [8].
In order to resolve this problem many manufactures offer *rail-to-rail* operational amplifiers, i.e., those that can give + V_{CC} and – V_{ee} at the output [9], [10], because the serial resistor has been eliminated (Fig. 20).

4.3 Troubles in the Initial Circuit

Fig. 11 and Fig. 12 depict the electronic schematic of the circuits that suffer the worst consequences of the *not-rail-to-rail* capacity. The *10V* input should be very accurate and never lower than 10V. Nevertheless, because of the limitation in the output range of previous amplifiers, this voltage was nearly 9V and the circuits depicted in Fig. 11 and Fig. 12 did not work properly.
It was not possible to obtain the correct voltage levels. This is, 5V – x and 0V + x instead of +5V/0V in the output *in Filtre* of Fig. 11, or 10V – x and -10V + x instead +10V/-10V in the output *vers Actionneurs* of Fig. 12. x always took a value of several milivolts.

5 The Solution: New Operational Amplifiers with Rail-to-Rail Capability

As soon as the problem was identified and in order to fix it, all the amplifiers were substituted by LF353 which has the *rail-to-rail* feature [11]. LF353 output stage is depicted in Fig. 20.

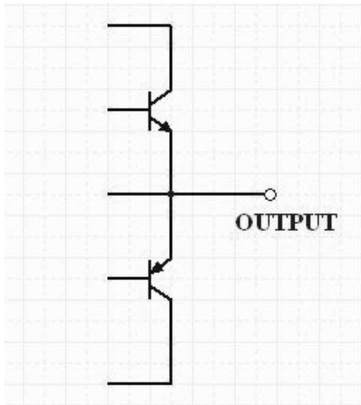

Fig. 20. Output stage of LF353 operational amplifier.

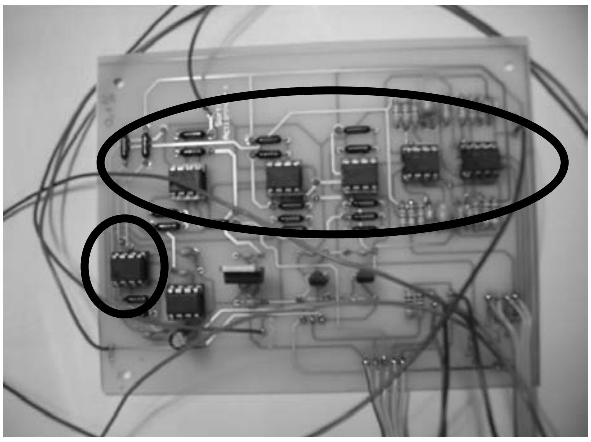

Fig. 21. Electronic card described in Section 2.2, where it is possible to see all the operational amplifiers.

In this way, the entire system worked properly and it is being used successfully in the Control courses for engineers, in the second and third academic years of ESTIA. The experimental setups were selected in order to teach control in several engineering fields with different dynamics such as in hydraulic, thermal and mechatronic process, as it has been mentioned before.

6 Conclusions

The *rail-to-rail* capacity is seldom among the most important features of an operational amplifier (symmetry of the power voltages, offset, CMMR, gain, input impedance, output impedance, frequency response, polarization currents, etc.). It means that the output range is equal to the power voltages (positive and negative or zero) without any offset.

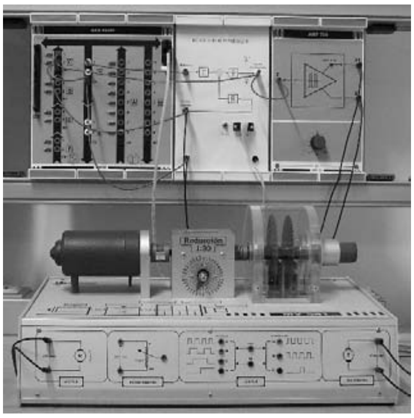

Fig. 22. Discrete Time Control didactical setup made in ESTIA.

The performance of the system sometimes does not depend on that feature, since it operates far enough from the limits of the output range or the offsets are negligible.

On the other hand, the *rail-to-rail* capability is crucial in accurate systems, like instrumentation ones, not to degrade the performance.

In our case, a circuit to perform some discrete time control algorithms needed a maximum output range for the system to work properly. With the initial operational amplifiers, the performance was not adequate. After setting *rail-to-rail* ones the problem has been resolved.

7 Acknowledgment

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