Development of an Instrumentation and Data Acquisition system based on a low cost microcontroller Arduino.

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Abstract
This thesis addresses the design, implementation and validation of an instrumentation system to be assembled on a prototype vehicle (HidrogenIST) built by a student’s team at Instituto Superior Técnico in Lisbon. The system would provide useful information regarding design techniques validation as well as overall performance for driver and vehicle monitoring and assessment. These types of systems are already available on the market, but it was noticed a market flaw of versatile and low cost instrumentation systems for academic and prototype’s usage. As a consequence, the design and implementation of such system within this work is considered very important.

The proposed system comprises two different modules. One of the systems is a strain gauge bridge based sensor comprising a data acquisition board NI USB-9237 (manufactured by National Instruments), which is used to acquire strain measures (from a Wheatstone bridge), amplify the signal and sending it over a Serial/USB interface to a personal computer (PC). The chosen solution has many advantages regarding electromagnetic noise (EMI) insulation as well as several dynamic specifications when compared to many of the homemade or “Do It Yourself” (DIY) products available. On the other end, the system includes another module which comprises a very versatile, low cost micro-controller, Arduino. Together with a Secure Digital (SD) card and a set of sensors such as accelerometers, encoders, potentiometers, instrumentation system with analog to digital conversion (ADC) and data storage was designed and built.

The system is implemented and tested on the HidrogenIST prototype at IST. The data acquisition system allows a sampling rate of about 750Hz at a data transfer rate of 20KB/s of information to the SD card. Albeit low cost and easy accessible based components, most of the components, as for example the accelerometers yielded a maximum error of 2% end of scale error, confirming both precision and sensibility criteria. However, strain gauge performance revealed a difference of 3% on calibration and laboratory tests and a difference of 20% on a real component taking as reference the equivalent Finite Element Method (FEM) model.

Keywords: Arduino, Strain Gauge, Accelerometer, Instrumentation System, Data acquisition

1 Introduction
Since the growth of computer calculus capability, accessibility and huge price decrease, it has become usual engineering practice the use of computer aided design (CAD3D) software to aid in the early stages of product design and even in product development phases. Such techniques yield good model results when compared with real models. The ability to match computer numerical simulations with real world system’s results enables the engineer/designer to be more confident in its design simulations.

This work is based on the existing prototype named HidrogenIST, a vehicle designed for the Shell Ecomarathon competition. Its features have been modelled with Solid Works, a CAD3D program, from which several Finite Element Method (FEM) simulations have been performed on. These numerical simulations allowed the designer to predict what type of parameters and their ranges of interest for acquisition purposes.

The development of an instrumentation system is a task which must certainly result in a compromise between dynamic vehicle monitoring and cost effectiveness. Such balance is very hard to guarantee, many times due to technical barriers (for instance electromagnetic noise-EMI) or sensors quality.

2 Requisites and Specifications
In the first step, let’s start by listing which parameters are truly of interest for their acquisition specifications, in the vehicle platform:

- Structural strain at relevant components;
- 3-axis Accelerations from -3G up to 3G with minimum sample rate of 45 Hz;
- Forward speed up to 100 Km/h;
- Angular position with range +/-15° at minimum of 50 Hz;
- Accelerator position;

The previous list of parameters is found to be relevant to improve dynamic performance of the vehicle/driver combination. In fact, the **HidrogenIst** vehicle is not a high performance vehicle in dynamic terms, but for fuel economy purposes a set of data details are of main importance to provide the driver with real time information related to his driving style.

On the other end, a set of information about structural performance let the designer to push the structural components more close to the limit, saving weight and fuel. In many cases the numerical simulations are not enough to provide designer’s confidence against his project. The balance and validation of numerical results with reality should be emphasized.

Secondly, there are installation criteria to be met. This concerns power supplies, environment interaction and data format. An instrumentation system (see Figure 1) must be portable a have a low power consumption of a few mA when powered at 12V. It must withstand some degree of humidity, sun light exposure and support vibrations generated by the moving vehicle. Its interaction with a PC must be flexible enough to allow fast data transfer rates and minimum hardware adaptors, preferably using standard laptop connections.

**Figure 1 – Arduino based data acquisition and storage system designed and built by the author**

Data acquisition is based on sensors, available in many types and shapes. In terms of accelerometers, a MicroElectroMechanical Systems (MEMS) type was chosen for this work after all the description made in (1) and (2). The MEMS accelerometers are highly available on the market with reasonable prices about 20€ featuring both static and dynamic measuring capabilities. The chosen accelerometers ADXL335, have an effective range of +/-3G with up to 50Hz in sampling rate. For strain measurements, foil type strain gauges were used which present the best cost effectiveness within strain gauge market. They also have a very low thickness and are available in a wide variety of sizes and shapes, being the most used for strain measuring, see (3), (4) and (2).

Data acquisition from strain gauges was accomplished with the use of a National Instruments (NI) USB 9237 (see Figure 2) acquisition board featuring a 24-bit differential ADC which converts Wheatstone bridge signals and sends them over a USB link to a computer (in this work a common personal laptop was used). To control the NI board the LabVIEW software (also from NI) was used.

All other sensors used in this work are connected with an **Arduino Mega** microcontroller. This controller has 15 analog ports connected to a 10bit ADC along with several digital ports enabling SPI and I2C communication protocols. It also has a programmable memory boot loader allowing user created code uploading. As a drawback, the ATMega processor shipped with Arduino does not possess floating point operation capabilities. Albeit not perfect, its major advantage is its cost. An **Arduino base** board costs about 20€ and the **Mega** version, with extended analog and digital ports along with a faster microprocessor and more memory, still only stands as high as 41€.

With such versatility it’s the developer’s task ability to manage the **Arduino’s** resources in such a way to avoid overflows or slow down the program execution.

In the background, data connections, data storage and power supply must be as reliable and resistant as the rest of the instrumentation system. Technical requirements include high speed data transfer, simple wet effective electrical connections, enough capacity to store full working sessions capable of producing several files of up to 200 MB. Special emphasis was given to stability and also to data retrieval methods. After a search on the available market devices, the choice converges to one of the two formats: USB flash drive and Secure Digital (SD) flash card. In (5) and (6) there is also a market study on compact reliable permanent data storage formats. Although slightly more expensive and with a more limited market availability, a SD card based system was chosen based on its greater overall quality and writing speed when compared to the USB drive.

Regarding physical interface, both formats could be wired to the **Arduino** through Serial UART, SPI or I2C. For programming freedom and better interface control, decision was made to use the SPI interface. This enables the use the many open source libraries instead of developing program coding for many of the most basic operations. After a few laboratory and field tests, benchmarking indicates that
steady state operation sample rate is close to 750 Hz with a data transfer speed of about 20 KB/s.

Figure 2 - National Instruments strain gauge acquisition board

3 Experimental Results

3.1 Arduino based system

Several laboratory calibration tests have been performed on controlled environments to verify the correct working conditions of all sensors used in the data acquisition equipment. After all pre-test checklist items have been cleared, a set of tests with real-world operating conditions were conducted. Test runs with the HidrogenIST prototype vehicle were performed at IST - Lisbon. These tests provided data that allow the comparison of the signal noise generated at different speeds, as well as with lateral acceleration and forward speed influence on it. Along with this data the overall system and subsystems were tested.

On Figure 3, one can see acceleration before and after filtering along with time evolution for both steering angle and throttle position. It should be noted that the filtering operation also smoothens the overall spectrum and acceleration amplitude decreases. As this field test aim was system testing and not data processing, it was decided to not pursue a better filtering algorithm.

Figure 3 - Unfiltered and filtered acceleration, steering angle and throttle position

A close look at the same figure shows an offset on the z axis acceleration. This effect is due to the low cabling quality used. The cables in question do not have EMI insulation and its length is not the same for each cable. Different lengths in the cables yield different internal resistances, and as a consequence the accelerometer output is proportional to resistance variation. Therefore, cable length creates a constant virtual acceleration.

Figure 4 - Y axis acceleration measured at 3 different locations

After the first test runs, several modifications were introduced on the instrumentation system. A speedometer with a digital display and a digital connection to the Arduino Mega was installed on the prototype. Wire connections and cables were improved although still remaining unshielded. An example of the second test run's data is shown on Figure 4. In this graphical representation, it should be noted the acceleration peaks, achieved with -12º steering angle and average speeds of 24 km/h.
The filtering parameters were also tuned to have less effect on acceleration amplitude. Such difference is visible on Figure 5. As one can easily notice, filtered acceleration value is approximately in the middle of the noisy band spectrum. This can be the proof that the previous amplitude problem is almost non-existing.

As previously mentioned, measuring EMI and road surface noise generation were on the list of the test objectives. Unfortunately it wasn’t possible to conduct any experiment that could separate EMI generated noise from road surface. To accomplish that objective, one would have to guarantee the ability to follow a predefined path along a defined surface at a certain speed and then repeat the same path at different speeds while measuring generated noise. Since the surface is the same, road noise would only change in frequency, which is known because it is the same as of the spinning wheel. The reason why EMI generated noise can’t be done in a laboratory is because the wheel would be spinning at a higher speed consuming considerably less power and the generated electromagnetic field (EMF) would be different from the real one. On Figure 6, the sum of both mentioned noise generation sources is represented for three different forward moving speeds. At the instant time where these measurements take place the acceleration on the vehicle was null.

### 3.2 NI9237 board based system

Finally, the strain gauge data acquisition system was mounted in the laboratory in order to acquire the strain values at selected locations on a mechanical component. This component is assembled on the HydrogenIST’s steering mechanism (located on the vehicle’s rear) and has been into service for about two years. The experiment’s goal is to compare measured strain values due to a known force loading against numerical simulation strain results. For that purpose, the work is based on the already existing SolidWorks (SW) model to run a Finite Element Method (FEM) simulation using the same loads and boundary conditions as the real component. All simulations were accomplished with the SW Simulation module. The mesh with their details can be seen on Figure 7.

A general view of strain distribution is available on Figure 8 while on Figure 9 one can have a general view of the experimental setup.

On the above mentioned figure, the wiring connection is done with a breadboard. This setup turned out to be very noise sensitive and a junction-box solution was implemented to improve quality results. This new setup also prevents bad wiring and reduces the risk of damaging the NI board. The experimental setup
was tested several times. The achieved results are detailed and plotted on Figure 10.

Figure 8 - Strain distribution results for a 30.5N load

Figure 9 - Component, acquisition board and loading weights

The first noticeable feature of the mentioned figure is that both evolutions are linear. This indicates a correct material behaviour and good gauge adhesion to the surface. However, these straight lines are neither coincident nor parallel. The difference which causes such effect is called gain error as opposed to an offset error which would easily be compensated by the acquisition board, (7). On

, relative error is shown to be approximately 20%.

Table 1 - Comparison between experimental and simulation results

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<th>Load [N]</th>
<th>Predicted</th>
<th>Experimental</th>
<th>Absolute error</th>
<th>Relative error [%]</th>
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Despite the relative error upper bound at about 20%, these still valuable information. To fully understand why a two digit error is still acceptable, one should take in account the following facts:

- automatic meshing method was used in SW with no manual tweaking;
- Mechanical component is part of a steering mechanism on a vehicle that has no suspension at all and has already been in service for almost two years;
- The part was milled from an aluminium plate which in its fabrication process is pressed in order to reduce thickness and increase length. Such process creates a residual stress state in which is not known. The materials properties changes (for example Young’s Modulus) and the material may no longer be isotropic.
4 Conclusions

Starting by the latter mentioned tests, there is an important remark to be made. The measured deformations are larger than predicted by numerical simulations, for the reasons previously mentioned. This is an undesirable situation as it means that the designer is designing a structure based on some loading and restraints conditions, obtaining a stress and strain distribution with values below real ones. This puts the designer solution with stiffer performance than the real one. Also the real stress distribution can lead closer to potential structural failure and it is up to the designer to apply a safety factor in order to account for unpredictable results.

On the other hand, testing with the Arduino system wielded very good results with good correlations observed between lateral acceleration, forward speed and steering angle. There are still technical issues to be addressed, as explained below, but we were able to establish solid grounds for further system expansion proving that a low cost system isn’t a synonym for bad precision or faulty electronics.

Finally, it is important to stress a few suggestions for further improvements, which were not carried out only due to some logistical issues. One of such improvements is a GPS position receiver. When trying to fully understand the vehicle’s operational situation, those efforts were almost fruitless due to the large amount of data involved. The vehicle’s location superimposed on a map would reveal several details such as terrain gradient, turning radius or distance covered. Other improvements range from a telemetry module, to better shielded cabling or thoughtful casing and positioning of all electronic components installed on the vehicle.

5 References


