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To cite this article: K Yubonmhat *et al* 2019 *J. Phys.: Conf. Ser.* **1380** 012012

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## A low-cost Arduino-based NMR console

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**Abstract.** Time domain nuclear magnetic resonance (TD-NMR) is a non-destructive technique to investigate a samples' physical properties, such as fat and water contents, porosity, viscosity and water states in cell compartments etc., by analysis of the samples' proton relaxations. However, commercial NMR consoles are still expensive, closed-source and unable to be customized for various applications. In this work, we demonstrate a low-cost, easy-to-build and customizable Arduino-based NMR console. The Arduino Due was chosen due to being easy-to-program while delivering high performance. The Arduino conducts four important functions i.e. controlling an RF synthesizer, timing control, data acquisition and PC interface. The NMR console is equipped with a quadrature modulator for RF phase control and a demodulator for signal phase detection. A low-cost HF power amplifier is used to amplify the transmitting signal, while a low noise amplifier TB-411-6+ is combined with an adjustable gain amplifier AD603 to amplify the received signal. The amplified signal is demodulated and collected by the Arduino. The console was successfully used to measure relaxation times of glycerin and mineral oils. The overall cost of the prototype console is approximately 363 USD. The quadrature modulator and demodulator are the key components for future development to be an NMR imaging console.

### 1. Introduction

Nuclear magnetic resonance spectroscopy (NMRS) is a technique widely used to analyze molecular structure and some physical properties of samples, by observing the local magnetic field surrounding atomic nuclei of the samples' molecules. NMRS can be classified into 2 types i.e. Fourier transform NMR (FT-NMR) or chemical shift and time domain NMR (TD-NMR) or NMR relaxometry. The chemical shift is a powerful tool for molecular structure analysis and needs an extremely high and homogeneous magnetic field, combined with a very high sensitivity detector; consequently expensive and delicate superconductor technology is necessary. In contrast, the TD-NMR based on an analysis of NMR relaxation can be used to investigate some physical properties of samples, such as porosity [1], oil content in sand rock [2], moisture [3], viscosity [4], flow and diffusion [5], cell size distribution [6] and sugar content [7] etc., since TD-NMR can be performed at low field and needs a less sensitive probe, causing a

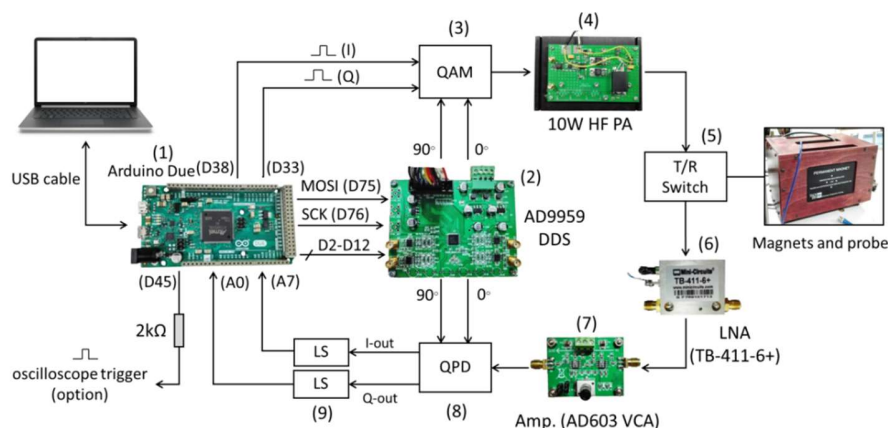


TD–MR system price to be much cheaper than the chemical shift spectrometer. An important advantage of the low field NMR (LF–NMR) is its ability to be carried outside for offsite experiments, such as offsite plant investigations [8], Antarctic ice structure research [9] petroleum exploration logging NMR [10] etc.

An NMR console is an important part of an NMR spectrometer and is usually expensive, closed–source and unable to be customized. Self–constructed NMR consoles allow more flexibility for researchers to design their NMR applications on a lower budget [11–14]. Field–programmable gate arrays (FPGAs) have become highly interesting for the main components of NMR consoles due to their ability to run in real time, have parallel controls and perform real–time data processing [12, 15–17]. However, the main drawback of the FPGA is its programming difficulty. For many researchers, electronics and programming skills are still the main obstacles to building an NMR console. In this work, we propose a solution to reduce the electronics work and programming difficulty for building an LF–NMR console. For the analog part, a set of low–cost electronic modules which can be found on an e–market are used. Our system provides a quadrature modulator for phase control and a quadrature demodulator for phase detection. These key components are useful for future development of the console to an NMR imaging console. For the digital part, a popular and easy–to–program Arduino Due microcontroller is chosen. The Arduino conducts four important functions i.e. controls an RF synthesizer, timing control, data acquisition and PC interface. A tiny data acquisition PC program to collect data from the Arduino was developed using visual C# 2013 express. A simple pulse sequence design method and programming is proposed. Basic pulse sequences to measure relaxation times, Carr–Purcell–Meiboom–Gill (CPMG) and inversion recovery (IR) were developed and tested with a permanent magnet of 0.5T.

## 2. Materials and methods

### 2.1. Hardware

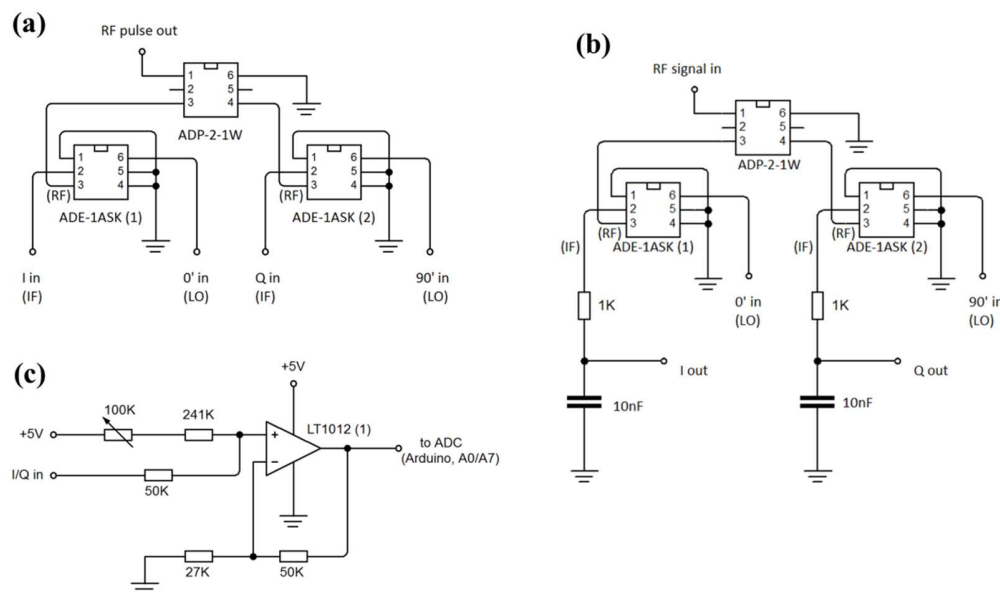


**Figure 1.** Diagram of the NMR console with real pictures of its components.

A diagram of the NMR console with real pictures of its components is shown in figure 1. The components consist of (1) an Arduino Due development board, (2) an AD9959 direct digital synthesizer (DDS) module, (3) a quadrature amplitude modulator (QAM), (4) a 10–Watt RF power amplifier, (5) a quarter wavelength T/R switch, (6) a TB–411–6+ low noise amplifier (LNA) (Mini–circuits), (7) a voltage controlled amplifier (VCA), (8) a quadrature demodulator or quadrature phase–sensitive detector (QPD) and (9) two level shifters (LSs). In this work, the NMR console was tested with a permanent magnet 0.49T

(21 MHz) with an RF probe (TeachSpin, New York USA). Details and functions of each component are as follows.

The Arduino Due performs four important functions i.e. PC interface, AD9959 control, timing control and data acquisition. The USB native port of the Arduino is used for communication with the PC due to its higher data transfer rate than the programming port. The AD9959 DDS is controlled via the Arduino serial peripheral interface (SPI) with an additional 11 digital I/O pins (D2–D12) to generate RF reference signals. The DDS has four independent outputs for frequency range 0 to 200 MHz and maximum output voltage of 2.2 V<sub>pp</sub>. The digital pins D38 and D33 are used to drive the in-phase (I) and quadrature phase (Q) pulse switching signals, respectively. The trigger signal (pin D45) is optional for oscilloscope observation.



**Figure 2.** Schematic diagram of (a) the QAM, (b) the QPD with two RC LPFs and (c) LS.

In the transmitting part, the QAM consists of a power combiner/splitter ADP-2-1W (Mini-circuits) and two double balanced mixers ADE-1ASK (Mini-circuits) as shown in figure 2(a). The modulated pulse is amplified by the 10-Watt power amplifier before transmitting to the probe. The power amplifier is a high gain (40dB) two-stage amplifier operating over a frequency range of 0.5 to 55 MHz. The quarter wavelength T/R switch is a 2.46 m length coaxial cable with two sets of crossed diodes (1N4148). In the receiving part, the TB-411-6+ LNA of gain 21.8 dB with operation range of DC to 2 GHz and noise figure of 2.3 dB is the first amplifier. The signal is then amplified by the VCA which consists of dual AD603 (Analog Devices) cascaded to yield a maximum power gain of 80 dB. The amplified signal is then demodulated by the QPD which has the same components as the QAM with an additional two RC LPFs, 15.9 kHz cutoff frequency, at each output as shown in figure 2(b). The I and Q signals are then level shifted up to fit the range 0 – 3.3 V of the Arduino analog to digital convertor (ADC) before feeding to analog input pins A0 and A7 of the Arduino. The level shifter circuits are shown in figure 2(c). The digital signals are then sent to the PC. The total cost of the hardware used in this project is approximately 363 USD.

## 2.2. Software

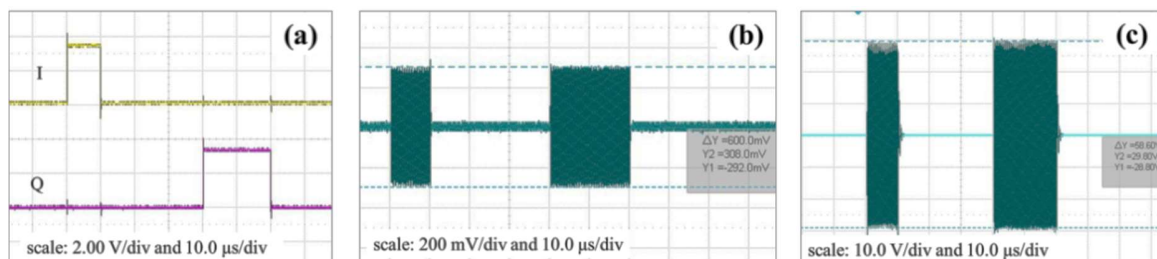
The software consists of two parts i.e. a data acquisition program (running on Windows 10) and an Arduino sketch including necessary libraries. The acquisition program was developed using Microsoft Visual C# express 2013. The program has two duties i.e. sending text commands to the Arduino and receiving NMR data as an array of 16 bits integers or a text message from the Arduino. The second part, the Arduino sketch, consists of a main sketch with five core libraries and four pulse sequences (as C++ libraries). All programs, sketches and all library source codes and their details are shared on GitHub [18]. A compiled pulse sequence will be kept as an array of events on the Arduino. The array will be used to run the sequence by an Arduino timer counter. In this work, the timer 2 of the Arduino is used to control the sequence timing. The timer's clock source is pre-scaled by 8 from the system clock 84 MHz to 10.5 MHz which gives time resolution of 0.095  $\mu$ s. Data communication protocol between the Arduino and PC is by a virtual COM port. Text commands with or without parameters are sent from the PC to the Arduino, while the data sent back to PC can be either a reply message or an array of unsigned 16-bit integers (NMR signals). The Arduino Due has a 12-bit ADC of conversion rate 1 Mega samples per second (Msps) and 3.3 V internal reference. In this work, the ADC is shared by two analog input channels, thus the maximum acquisition speed is 500 ksp/s. The ADC is run at the maximum speed while the data collection rate is adjusted using an interleaving technique. The ADC buffers are set to 10,000 points per channel.

This console was tested to measure  $T_1$  and  $T_2$  relaxation times of glycerin and mineral oils using the IR and CPMG pulse sequences. The input and output signals of each module were investigated. The performance limitations of the Arduino Due were investigated.

## 3. Results and discussion

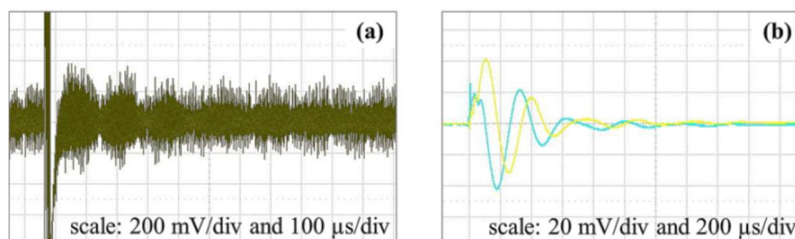
### 3.1. Analog signal quality

In the transmitting part, small induced spikes interfering between the I and Q pulse switching signals (pins D38 and D33) were observed, as in figure 3(a). The voltage of the reference signals from the AD9959 module was reduced to 1.0 V to match the requirement of the ADE-1ASK mixers. The RF pulses output from the QAM had a high background noise of about 50.0 mV<sub>pp</sub> (8.3% of the pulse voltage) as shown in figure 3(b). The noise is a mixed of the reference signal and a DC offset found on the I pulse switching signal (pin D38). However, after the pulses were amplified by the power amplifier the noise ratio to the pulse amplitude were significantly reduced, as shown in figure 3(c). The noise was automatically filtered out since its power is less than the minimum limit of 0 dBm (1 mW) of the power amplifier. The real voltage gain of the power amplifier is approximately 10 dB. Another issue found for the power amplifier is that the output signal is distorted when feeding a supply greater than 6.9 V.



**Figure 3.** Transmitting waveforms: (a) I and Q pulses switching from the Arduino, (b) 90° I-pulse followed by 180° Q-pulses output from the QAM and (c) the pulses after being amplified by the 10-Watt power amplifier.





**Figure 4.** FID of glycerine: (a) FID amplified by the AD603 module and (b) the demodulated I (yellow) and Q (blue) signals output of the QPD.

Figure 4(a) is a free induction decay (FID) of glycerine, output from the AD603 module. The tail of the excitation pulse appears as a relatively large signal at the beginning of the FID. Too high gain of the AD603 module induces too much noise and causes the NMR signal to disappear. Figure 4(b) shows the demodulated I and Q signal outputs of the QPD. The output I and Q voltages are of the order of 70 mV<sub>pp</sub>. The level shifters also amplify the voltage of the shifted signals slightly by about 2.35 times, compared to the theoretical gain of 2.85 times.

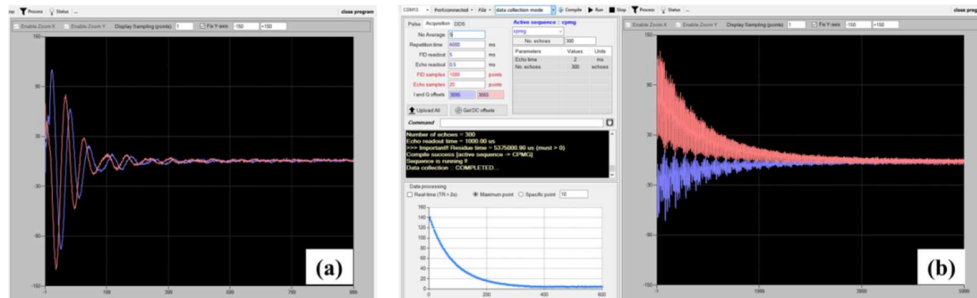
### 3.2. The Arduino Due performance

In this project, the timer resolution of 0.095  $\mu$ s is enough to control time parameters of the order of microseconds, such as the RF pulse width. The best time resolution that the Arduino Due can produce is 0.024  $\mu$ s, at a clock speed of 42 MHz. For our program, the Arduino CPU needs approximately 1.62  $\mu$ s to change pin state and update the timer register. Thus 1.62  $\mu$ s is the lower limit of any time parameters. To avoid accidental error, the time limit is set to 2.0  $\mu$ s; consequently the test sequences can be run with excellent stability. For data communication, the heaviest duty is sending the big integer arrays of NMR signals to the PC. From a simple test of sending 10,000 bytes of data to the PC we found that the average data send out rate of the Arduino is approximately 7.1 MB/s, however the rate is highly irregular. The data receiving rate of our data acquisition program on the PC (using the Virtual COM protocol) is about 10 times slower than this rate. To improve the transfer rate, a better data transfer protocol is needed. According to the irregular data transfer rate, data transfer during the running sequence is unable to prevent the sequence running Failure. Thus, a large memory is needed to accumulate FID or echo data and transfer them at the end of the sequence. The Arduino Due has a total of 96 kB SRAM. Data buffers and the events array of the pulse sequence are the major RAM consumers. In this work, two buffers of 10,000 points for I and Q signals need 40 kB SRAM and the array of 4096 events need 48 kB SRAM; a total of 88 kB is used. With this memory, management of the CPMG, the longest sequence, with 1000 echoes (10 points/echo) is achieved. The ADC speed at 500 kps is enough to sample FID and echo signals of the order of a millisecond or longer. To improve the Arduino Due performance, data transfer using dynamic memory access (DMA) which can free the CPU from the data transfer, might allow data transfer while the sequence is running so that longer data trains could be collected with the limited buffers.

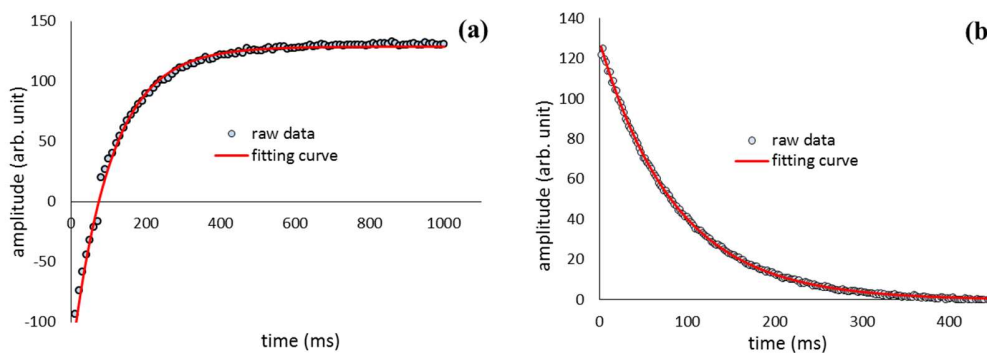
### 3.3. Relaxations measurement

Figure 5 shows screen capture of the data acquisition software. Figure 5(a) is I (in blue) and Q (in red) FIDs of glycerin acquired using the tuning sequence while figure 5(b) is a 300 echoes train of the CPMG sequence of glycerin. Magnitudes of the I/Q echoes are used to calculate the  $T_2$  relaxation time of glycerin. Figure 6 shows examples of  $T_1$  and  $T_2$  relaxation curves of glycerin. It was found that the obtained data points near zero amplitude are scattered due to the NMR signal approaching noise level, as shown in figure 6(a). The measured  $T_1$  relaxation times of glycerin, light mineral oil and heavy mineral oil

are 105.3 ms, 82.1 ms and 38.6 ms and the  $T_2$  relaxation times are 86.6 ms, 71.9 ms and 30.1 ms, respectively.



**Figure 5.** Screen capture of the data acquisition program shows I (blue) and Q (red) NMR signals of (a) an FID of glycerin and (b) the 300 echo train of the CPMG sequence of glycerine.



**Figure 6.** Relaxation curves fitting of NMR data of glycerin obtained by using (a) the IR pulse sequence and (b) the CPMG pulse sequence.

#### 4. Conclusion

The popular and easy to program Arduino Due has a role as the main part of an LF-NMR console. The Arduino timer can provide timing control precision of the order of sub-microseconds. The Arduino ADC speed is enough to sample FIDs or echo signals of the order of a millisecond or longer. Low-cost electronics modules from e-markets can replace the analog parts of the LF-NMR console and significantly reduce electronic work. Our Arduino-based low-cost NMR console was successfully used to measure relaxation times of samples, however there still some of both analog and digital parts that should be improved. According to the ease of programming the Arduino Due, the console is easy to customize for various LF-NMR applications. The quadrature modulator and demodulator are the keys for the future development of the console for NMR imaging in future work.

#### Acknowledgments

This work was financially supported by the Science Achievement Scholarship of Thailand (SAST) and the National Research Council of Thailand (NRCT), project number: 2561A10302235.

## References

- [1] Esmaili M, Shadizadeh S R, Habibnia B, Ghoghogh J N, Noruzi–Masir B and Bakhshi P 2017 *Appl. Radiat. Isot.* **130** 172
- [2] Lo S W, Hirasaki G J, House W V and Kobayashi R 2002 *SPE J.* **7** 24
- [3] Bertram H C, Andersen H J and Karlsson A H 2001 *Meat Sci.* **57** 125
- [4] Ribeiro R d O R, Mársico E T, Carneiro C d S, Monteiro M L G, Júnior C C and Jesus E F O d 2014 *J. Food Eng.* **135** 39
- [5] Nagata A, Kose K and Terada Y 2016 *J. Magn. Reson.* **265** 129
- [6] Geya Y, Kimura T, Fujisaki H, Terada Y, Kose K, Haishi T, Gemma H and Sekozawa Y 2013 *J. Magn. Reson.* **226** 45
- [7] Pereira F M V, Carvalho A d S, Cabeça L F and Colnago L A 2013 *Microchem. J.* **108** 14
- [8] Musse M, Leport L, Cambert M, Debrandt W, Sorin C, Bouchereau A and Mariette F 2017 *Plant Methods.* **13** 53
- [9] Callaghan P T, Eccles C D, Haskell T G, Langhorne P J and Seymour J D 1998 *J. Magn. Reson.* **133** 148
- [10] Behroozmand A A, Keating K and Auken E 2015 *Surv. Geophys.* **36** 27
- [11] Michal C A 2010 *Meas. Sci. Technol.* **21** 105902
- [12] Hemnani P, Rajarajan A K, joshi G and Ravindranath S V G 2016 *Procedia Comput. Sci.* **93** 161
- [13] Utsuzawa S and Fukushima E 2017 *J. Magn. Reson.* **282** 104
- [14] Hibino Y, Sugahara K, Muro Y, Tanaka H, Sato T and Kondo Y 2018 *J. Magn. Reson.* **294** 128
- [15] Takeda K 2008 *J. Magn. Reson.* **192** 218
- [16] Tang W and Wang W 2010 *Meas. Sci. Technol.* **22** 015902
- [17] Chen H Y, Kim Y, Nath P and Hilty C 2015 *J. Magn. Reson.* **255** 100
- [18] Saowadee N 2018 *Arduino\_NMR* Online: [https://github.com/nsaow/Arduino\\_NMR](https://github.com/nsaow/Arduino_NMR)