ZK
48

Technical Documentation

48 Output Programmable Wired Pyrotechnic Ignition System based on the ATTINY 861

by Markus K. 2023

Contents

1 Introduction

The ZK-48 ignition (German "Zündkasten 48 Ausgänge") system was developed, because of a lack of affordable programmable firing systems. Therefore the development began for a low cost, yet reliable and robust device, that works in any condition. This document provides all information surrounding this project and anyone with basic knowledge in electronics should be able to rebuild it for them self. Although this should not be viewed as an instruction, on how to build this device, the author hopes it will be useful to a pyrotechnic and or electronics enthusiast. The finished device is shown in Figure 1 with the trigger on the right and one ignition module on the left.

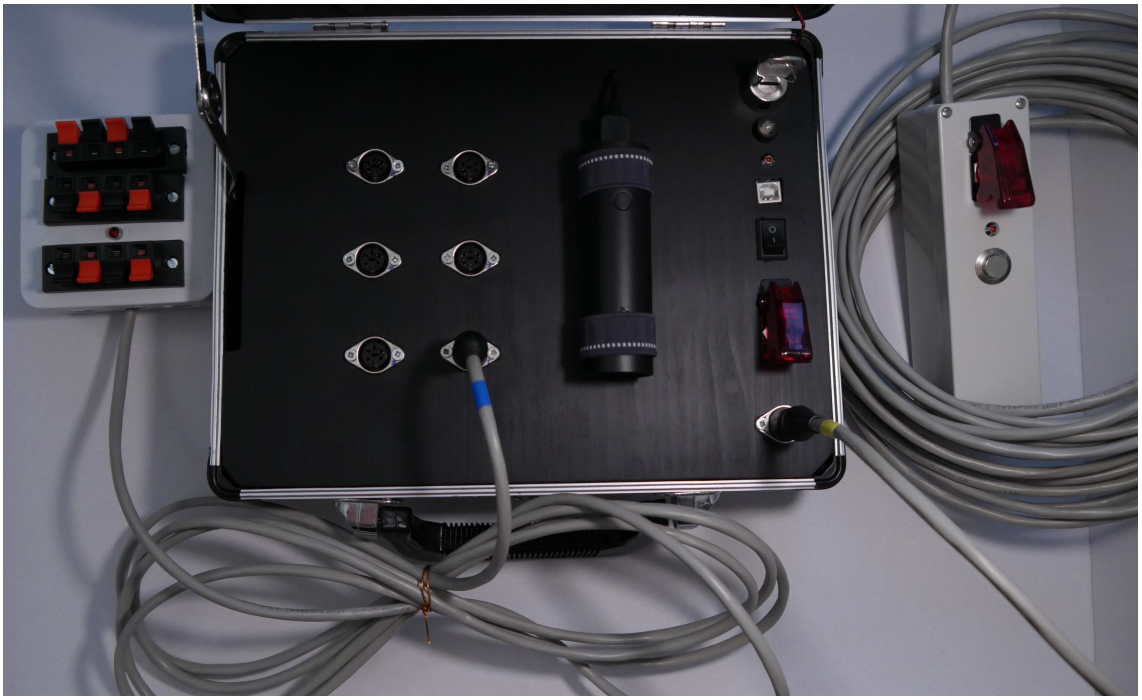


Figure 1: The complete system with trigger and one ignition module.

1.1 Legal Disclaimer

Please check your local laws before you decide on building a system such as this, by your self! Some countries may have laws prohibiting the construction of home-made ignition systems. So get informed! The author of this document does not endorse illegal activities, nor can he be held responsible for any person's illegal activities. According to Austrian law, to which the author is subject, the construction and use of self-made ignition systems in the private and professional sphere is *not* prohibited! This is not legal advice, so do your own research!

In this document electronic ignitable matches are sometimes refereed to as *Bridge wire detonators* or also short *detonators*. However, this does not mean actual detonators (also in English called *blasting caps*) are used, as they contain high explosives which are not legal, without license, in Austria! The author refers to the in Austrian/German called "A-Typ Brückenzünder"[1] which are legal to purchase by anyone who is over 18 years of age. Again, this is not legal advise and do proper research on your local laws!

[1] https://de.wikipedia.org/wiki/Br%C3%BCckenz%C3%BCnder

1.2 Concept

The device is divided into four subunits: controller, ignition voltage generator, trigger and ignition module, as seen in Figure 2. On board the controller, which sits in the middle, are all user input elements, sockets for connecting the peripheral devices and inside the controller are the circuits that coordinates everything. The trigger is connected by cable to the controller and is used to start the pre-programmed pyrotechnic show. There are six ignition modules, also connected to the controller by cable, and each module is able to ignite eight bridge wire detonators separately (A-Type Only). Therefore the complete system is capable of setting of 48 detonators with 48 steps in the pyrotechnic show.

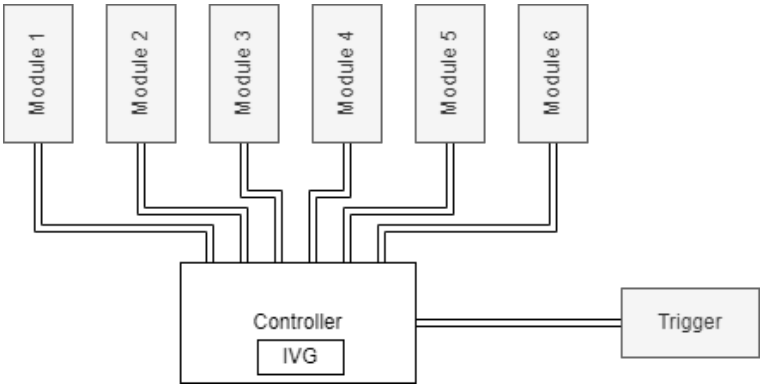


Figure 2: Basic layout of the three components: controller, trigger and modules.

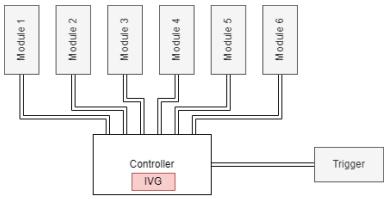
The system operates by the fire-and-forget principle. The user arms both the controller and the trigger and after pressing the trigger button the controller will automatically ignite the firework in the preprogrammed sequence. No user input is needed after starting the pyrotechnic show. When the trigger is pressed the system goes into a $10s$ delay phase, in order for the user to distance themselves from the device and get to safety, before the pyrotechnic effects are ignited. After the delay phase has ended, the ignition phase is entered, where the programmed sequence will play through until the predetermined endpoint is reached. The trigger could be replaced with a RF-trigger, although this is not recommend due safety and legal concerns in some countries. The delay phase also serves as a fail safe, because in the case of an accidental triggering of the system, the user is able to abort the start by disarming the system. During the ignition phase it is also possible to halt the program, by disarming the system, although re-triggering will repeat the delay phase.

As the device is most likely to be placed in an open-air field, there is no way for it to be connected to mains power, therefore it has to be operated by batteries. However, the usage of rechargeable batteries, such as LiPo-batteries, was not desirable for this project, due cost issues and the additional requirement of protection circuits. A better alternative was found by using common $5V$ portable powerbanks for smart phones. Those already provide steady $5V$ with build-in protective mechanisms. Furthermore, nowadays many people use powerbanks and if the user forgets to charge or forgets the powerbank altogether, there is a high probability some person will be able to provide one as replacement. A powerbank can be charged by a simple micro USB cable which is also very common and removes the need for a specialized charger.

2 Hardware

As explained in section 1.2, the device can be divided into four parts. This section will explore each separately by looking into the circuits, housing and all the design choices that led to the finished product.

2.1 The Ignition Voltage Generator



The ignition voltage generator shown in fig. 3 works by the basic principle of a step-up/boost converter, by storing energy in form of a magnetic field inside an inductor and releasing the energy as a current into a capacitor. Repeat this process at a high frequency and a high voltage is generated at the output. For a detailed explanation please read the document about this topic by *Texas-Instruments*[2].

2.1.1 Circuit

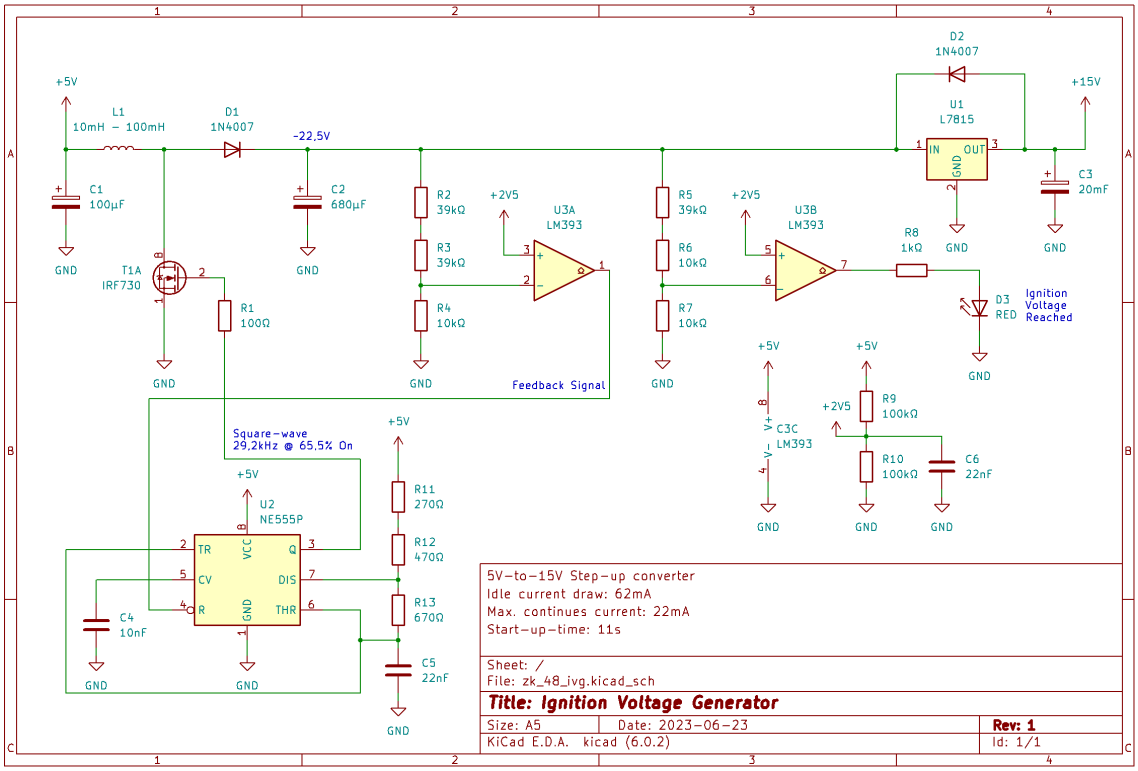


Figure 3: Circuit of the 5V-to-15V step-up converter.

[2] https://www.ti.com/lit/an/snva731/snva731.pdf

2.1.2 How does the circuit work?

The circuit shown in fig. 3 is based on the popular NE555[3], the dual voltage comparator LM393[4] and the fixed $15V$ linear voltage regulator L7815[5]. The NE555 is used as a square wave oscillator to generate a $29,2kHz$ $5V_{pp}$ signal with a $65,5\%$ on-time. This signal drives the IRF730[6] N-channel MOSFET, which switches current through the inductor $L1$ and therefore charging the capacitor $C2$. This voltage is named the intermediate voltage.

Through a voltage divider the voltage at $C2$ is stepped down by a factor of $\frac{1}{9}$ and compared to a $2,5V$ reference voltage by $U3A$. This results in a $5V$ output signal at the output of $U3A$, if the capacitors $C2$ voltage is lower than $22,5V$. This signal is called the feedback signal and is used to turn off the NE555, if the intermediate voltage has reached $22,5V$. Using a schmitt-trigger results in a oscillating feedback signal, which is undesirable in this configuration. If the intermediate voltage reaches $22,5V$, the feedback signal will no longer be $5V$ or $0V$, instead it will drop to a constant $2,5V$. This is expected as no schmitt-trigger is used, but will result in unpredictable behaviour by the NE555, as it expects a binary reset signal. This seems like a problem, but in reality will result in the NE555 output voltage to drop below the on-voltage of the IRF730, thus turning it off. It is also observable that the frequency and on-time of the NE555 output is rising, but this has no effect, because the voltage already dropped significantly to turn off the MOSFET.

The intermediate voltage is then converted by the L7815 to stable $15V$, which charges the large $20mF$ ignition capacitor $C3$. This voltage is called the ignition voltage. Equation (1) calculates the total energy stored in the system with all six modules connected (Thus the total capacitance being $26mF$, but read more in Section 2.4.2 "Additional circuits") which equates to around $3J$ and therefore does not pose any danger to life[7]. Touching the fully charged capacitors with wet hands (which is highly advised against doing!) did not result in any shock or pain.

$$W_{el} = \frac{U^2 \cdot C_{tot}}{2} = \frac{(15V)^2 \cdot 26mF}{2} = 2,925J \tag{1}$$

The second comparator $U3B$ in the LM393 package is used to turn on a red signal LED $D3$, whose purpose is to indicate whether the intermediate voltage is bigger than $14,75V$. This shows the user if the system is ready for operation and if ignition voltage is present.

[3] https://www.ti.com/lit/ds/symlink/ne555.pdf
[4] https://www.ti.com/lit/ds/symlink/lm393.pdf
[5] https://www.st.com/resource/en/datasheet/l78.pdf
[6] https://www.vishay.com/docs/91047/91047.pdf
[7] https://www.ehss.vt.edu/programs/ELR_capacitors.php

2.1.3 Testing

For testing the ignition voltage generator, displayed in fig. 3, a resistor with $4,7\Omega$ was placed into port 1 on module 1 (Please read section 2.4.2 for further information about the circuit shown in fig. 4). This resistance is about equal of two bridge wire detonators connected in series. A lower resistance would strain the ignition voltage more, but often more than one detonator is used in a pyrotechnic show, thus making it a bit more realistic. Figure 4 shows the complete test setup, with the pulse generator symbolically representing the controller. The system was programmed to fire(one fire pulse takes $10ms$) port 1 on module 1 eight times with a $10ms$ delay between each pulse.

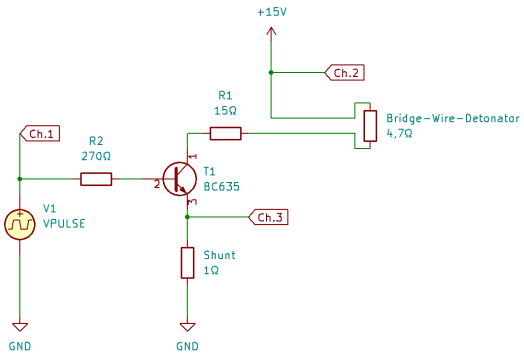


Figure 4: Circuit for testing stability of ignition voltage and current through a simulated bridge wire detonator.

2.1.3.1 Results

The first test consisted of 8 pulses to simulate fast consecutive firing of pyrotechnic single-shots[8] or other pyrotechnic effects. Normally firing the same port multiple times does not make sense, but for testing purposes this is equivalent to firing eight separate ports. The resulting waveform was captured with the Quad DSO (digital storage oscilloscope) *Rigol DS1054z*[9].

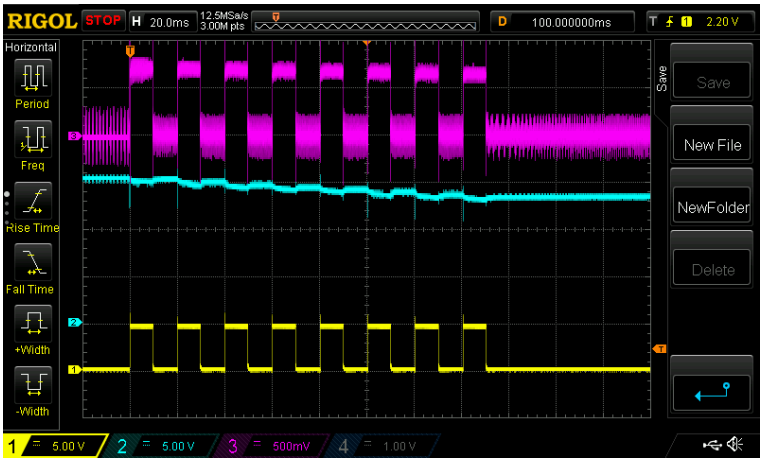


Figure 5: The recorded waveforms by the oscilloscope of eight pulses in close up.

The main objective of this test was confirming that rapid firing does not affect the systems ability to ignite further detonators. This can evidently be confirmed by looking at the curve of Ch.3 and Ch.2 in fig. 5. The ignition voltage is represented by Ch.2 which drops only by $2V$, thus being neglectable. By looking at Ch.3, which shows the current through the bridge wire detonator, it is noticeable that the current is above $700mA$, even at the last pulse. Past testing showed, bridge wire detonators already ignite at around $300mA - 400mA$. This confirms the efficacy and the systems ability to continuously ignite pyrotechnic effects at a high rate.

[8] https://www.youtube.com/watch?v=UgVG9NcA5CM
[9] https://www.batronix.com/pdf/Rigol/UserGuide/DS1000Z_UserGuide_EN.pdf

In fig. 6 the time was measured for the ignition voltage to return back to $15V$ after firing eight times. This time amounts to about $2s$ which is acceptable, but could be improved.

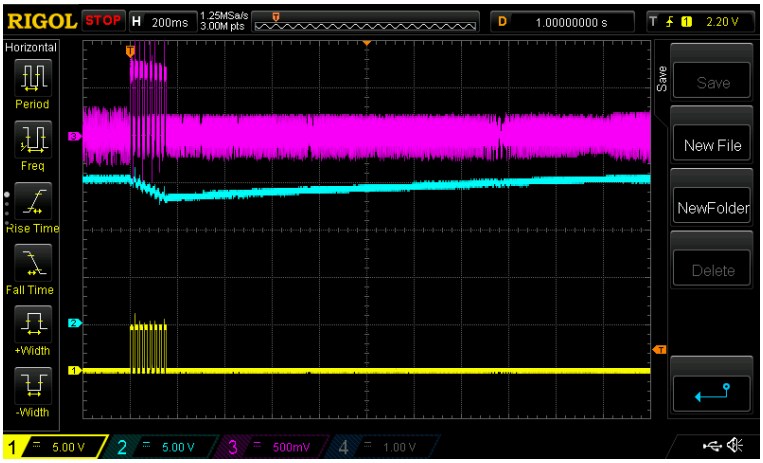


Figure 6: The recorded waveforms by the oscilloscope of eight pulses, until the ignition voltage returns to $15V$.

The third test focused on finding the absolute limit of the system. To achieve this objective the ZK-48 was programmed to use all its 48 sequence slots and fire port 1 on module 1 48 times.

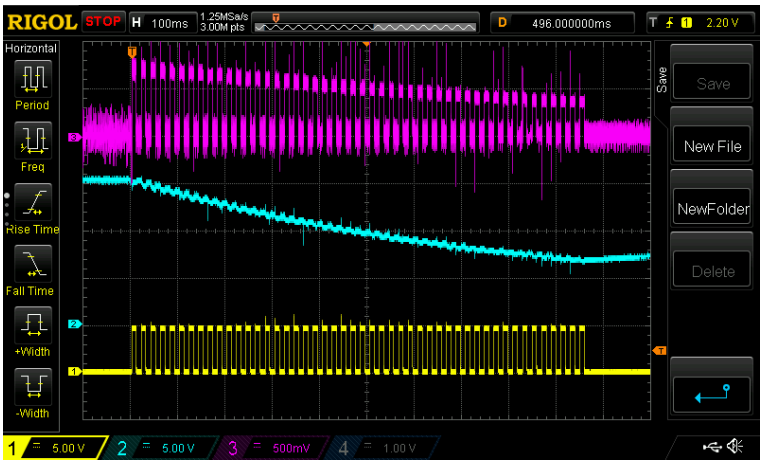


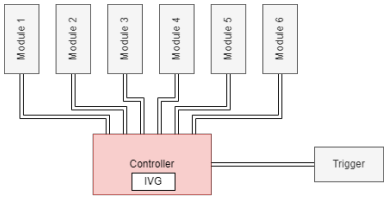
Figure 7: The recorded waveforms by the oscilloscope of 48 firing pulses.

The maximal number of firing pules was determined by counting the number of pulses until the current through the detonator fell below $500mA$. This current value was chosen because it is the average between the lowest recorded current at which a detonator ignites($300mA$) and the current at the first ignition pulse($700mA$). By this definition, the maximal number of consecutive firing pulses with $10ms$ delay is about 24.

2.1.3.2 Conclusion

The ignition voltage generator is able to provide a steady voltage, even under load(See fig. 4) and is able to ignite 24 bridge wire detonators consecutively with a $10ms$ delay. This is just theoretical and needs to be confirmed with real detonators, however this is already a good indicator for proper operation. Although the ignition voltage generator performs acceptably, it has many flaws and should be subject of rigorous optimization. For example, the ignition voltage should ideally not drop at all and remain constant even if continues $700mA$ are drawn. By using a bought step-up converter, with proper control logic, such as current regulation, instead of a simple feedback loop, most problems would be rectified. This projects goal is not buying electronic modules and soldering them together, instead this is an exploration of circuit design and should be viewed as a learning experience.

2.2 Controller



The controller is responsible for interpreting all user inputs such as the arm switch, the trigger signal and more which are processed by the µC to correctly control all modules to fire the pyrotechnic show. The ignition voltage generator is also soldered onto the same physical circuit board as the controller, but more about that in section 2.2.4.

2.2.1 Circuit

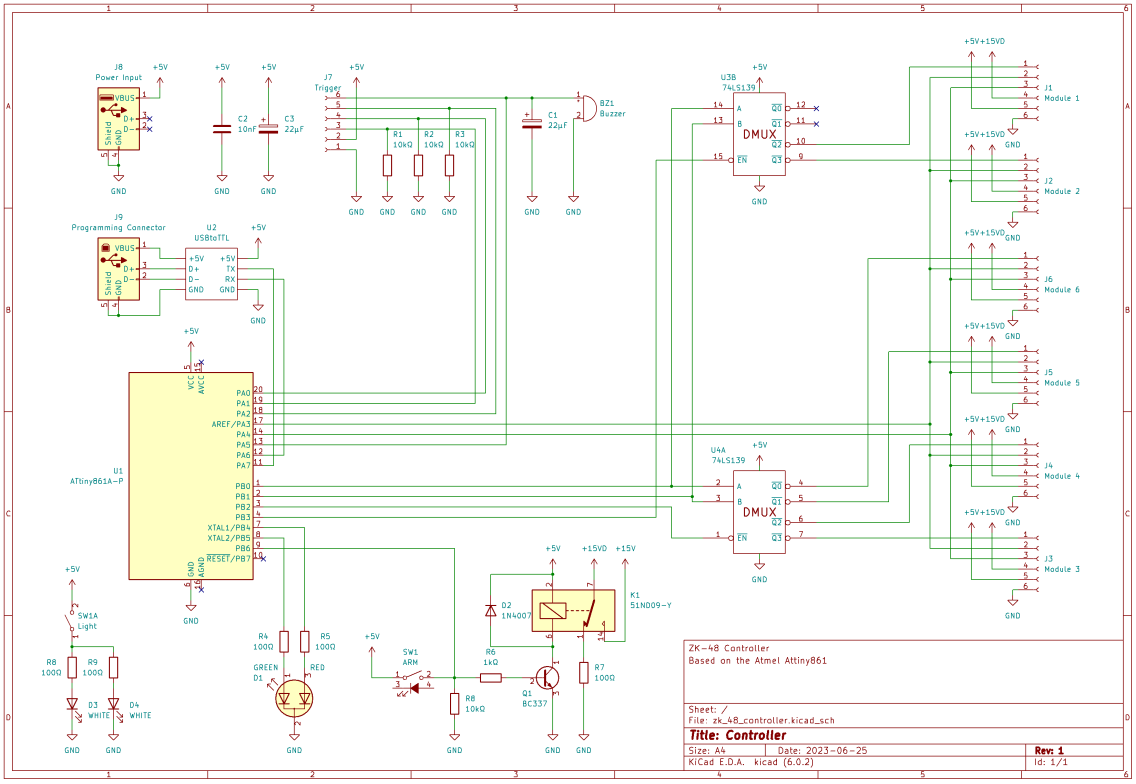


Figure 8: The circuit of the controller without ignition voltage generator.

2.2.2 Components of the Controller

The controller consist of the peripheral managing and controlling logic, the USB serial communication and the arm safety circuit.

2.2.2.1 Peripheral Managing and Controlling Logic

This part of the circuit is located on the right side of the circuit depicted in fig. 8. Its purpose is the selection of the correct ignition module to fire. To understand how this works, it is necessary to first explain how the µC fires a port on a module: In fig. 8 notice that all ignition modules sockets have their DATA and CLK lines connected together(For the pin-out see section 2.2.3). First, the µC serially transmits to all modules shift registers, at the same time, the port that is about to be fired. In the second step, the µC selects one out of the six modules, which then fires the port that was set in the first step.

The selection process of the ignition module is accomplished by two demultiplexer $U4A$ and $U3B$ which are both contained in the dual DMUX 74LS139[10]. Instructions are given to the DMUX by the µC. This circuit design only allows to select one module at a time, thus the system is unable to fire two ports on different modules at the same time. Although the firmware does not support simultaneous firing of to ports anyway. This is a disadvantage, but is manageable by programming the system to fire two ports with no delay, which results in a $10ms$ between each firing. The human eyes cannot pick up on such short delays and pyrotechnics are also not timed perfectly, therefore this does not pose a problem.

The socket of the external trigger also falls into peripheral circuitry, but it does not contain any logic. Resistors $R1 - R3$ pull down the sockets FIRE, ARMED and CONCD lines(For the pin-out see section 2.2.3). Those are inputs of the µC and are able to not have a defined potential, if the user unplugs the trigger when the system is powered on, therefore needing to be pulled down. The local signal buzzer $BZ1$ is wired to the sockets BUZZER signal and its voltage is stabilized by the capacitor $C1$. Without this capacitor, the sound of the buzzer is very unpleasant to the ear.

2.2.2.2 Attiny 861

The heart of the controller is the 8-Bit AVR micro controller (µC) Attiny 861[11]. Its most notable features are the 512 bytes in-system programmable EEPROM that stores the firing sequence, 16 I/O pins, the 8 kilobyte of program flash memory, as well as many more features. Further information will be provided in section 3.

2.2.2.3 USB serial communication

For programming the firing sequence, the µC has to communicate with a computer. As the Attiny 861 does not have in-build UART support, the TTL serial communication was used instead. This requires a device that translates TTL to UART and back, which is often done by a FDTI chip[12]. At the time where the hardware for this device was being build no FDTI chip or substitute chip could be obtained with reasonable pricing in the authors location. Therefore the decision was made to save time and money by buying a UART-to-TTL module of *Amazon*. As this is a bought, which is against the spirit of this project, this module it will be replaced in the near future, when a FTDI chip is obtainable.

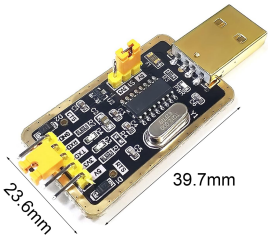


Figure 9: The bought UART-to-TTL converter from *Amazon*

Source of fig. 9: `https://amzn.eu/d/3QKPgB9`

[10] https://www.ti.com/lit/ds/symlink/sn54ls139a-sp.pdf
[11] https://www.mouser.com/datasheet/2/268/Atmel_2588_8_bit_AVR_Microcontrollers_tinyAVR_ATti-1315472.pdf
[12] https://ftdichip.com/

2.2.2.4 Arm safety circuit

This part of the controller circuit is shown in fig. 8 on the bottom and is very important. For safety reasons, the ignition voltage gets galvanically disconnected from the ignition voltage line of the modules, if the system is unarmed. Without this circuit, it is possible for a bridge wire detonator to ignite prematurely during power up or if a module is disconnected and reconnected.

The cause of this very dangerous behaviour is explained by the shift registers used in the ignition modules(See section 2.4). Most shift registers will, when connected to power, take on random values inside their internal registers. If the output is disabled through the *Output Enable* pin on the 74HC595(For further information see section 2.4.2 "Controlling the Ignition Circuits"), this could not happen. However those enable pins are driven by the DMUX on the controller (See fig. 8) and those DMUX are controlled by the µC. But a µC takes a lot longer to boot than a shift register. Thus for a very short period ($< 20s$) of time, turning on random outputs of the shift registers and making premature ignition possible.

Although this cannot be prevented in the firmware, it is possible to remove the ignition voltage and pulling down the modules ignition voltage line with a 100Ω resistor (See resistor $R7$ in fig. 8). The relay $K1$ is only connecting the ignition voltage to the modules power lines, if the controller arm switch is physically toggled on and therefore making it near impossible to accidentally set of pyrotechnics unintentionally.

2.2.2.5 Additional circuits

As the system will most likely be operated in the dark, the decision was made to add a small LED light inside the casing of the controller, to illuminate the interface. The circuit can be found in the bottom left corner in fig. 8, although the LEDs are not soldered onto the circuit-board. They are placed inside the lid(See section 2.2.5), shining downwards on the interface.

2.2.3 Sockets and Plugs

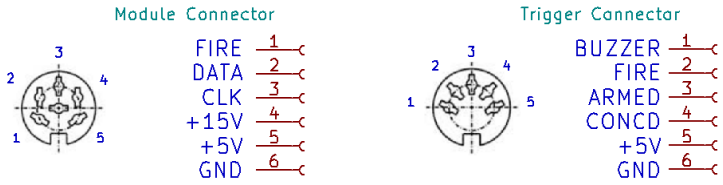


Figure 10: The pin-out of the trigger and modules socket/plug.

Source of the socket sympol in fig. 10: ***https://cdn-reichelt.de/documents/datenblatt/C160/MAB%205S-ROHS_XX.pdf***

To connect the peripheral devices to the controller DIN[13] plugs and sockets were used. The module socket and plug where chosen differently than the triggers, because accidentally plugging the trigger into a module socket would damage the triggers electronics. For the pin-out of each socket see fig. 10 and below in fig. 11 the modules socket and plug is visible.

Figure 11: The DIN socket and plug of the modules.

Source of fig. 11: ***https://cdn-reichelt.de/bilder/web/xxl_ws/C160/MAS_50.png***
Source of fig. 11: ***https://cdn-reichelt.de/bilder/web/xxl_ws/C160/MAB_5.png***

[13] https://en.wikipedia.org/wiki/DIN_connector

2.2.4 Circuit board

A perfboard with one sided solder copper pads with the dimensions of 100x115mm was used as the base for the controller circuit. Both the controller circuit (See fig. 8) and the ignition voltage generator (See fig. 3) were soldered onto the same board. Ideally, a PCB should be used to improve EMC, but this would make it difficult to change things in the future.

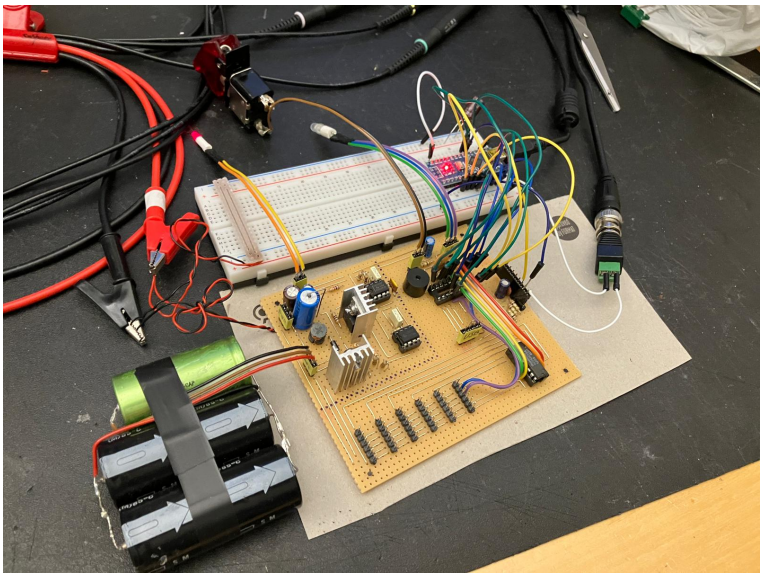


Figure 12: The controller circuit during development.

The ignition voltage generator is visible in the left top corner, with heat sinks mounted onto the MOSFET and voltage regulator. The right top corner contains the µC, all the pin-headers for connecting the switches, LEDs and the arm safety circuit. On the bottom, the peripheral managing logic is visible together with the six pin-headers for the modules.

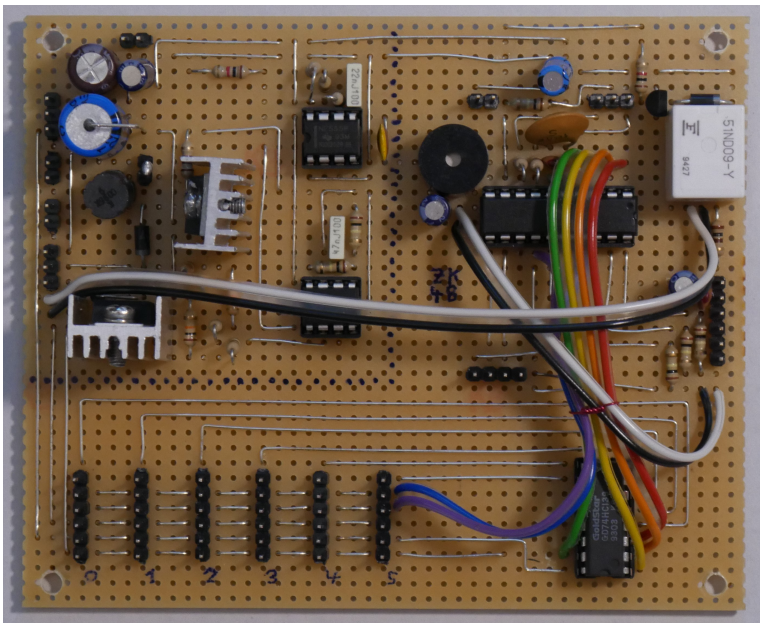


Figure 13: The controller circuit (See fig. 8) and the ignition voltage generator (See fig. 3) soldered onto a perfboard.

2.2.5 Housing of the Controller

The image in fig. 14 shows the controller circuit board with all peripheral items connected. On the top are the two big capacitors that store the ignition and intermediate voltage, secured to the board by a metal band.

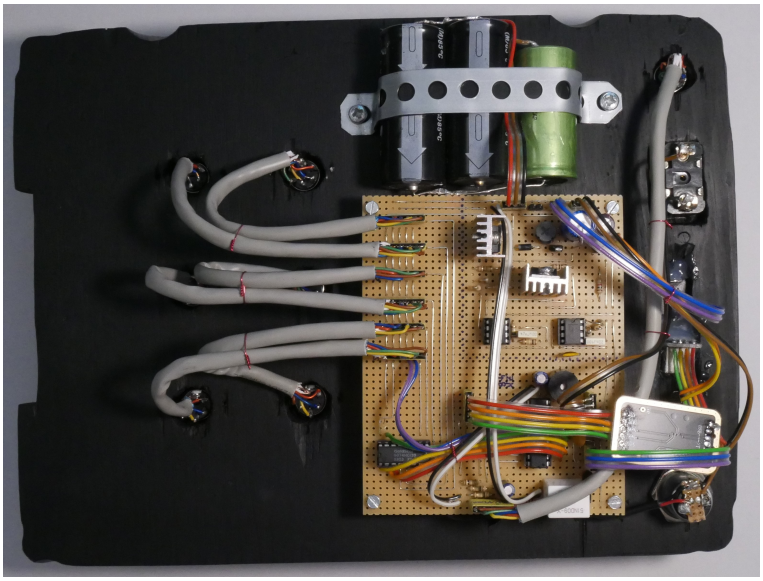


Figure 14: The circuit board depicted in fig. 13 mounted and wired onto the backside of the devices interface.

As the baseplate for the interface, a $2cm$ thick wooden plate was used. Holes were drilled to allow switches, status LED and the sockets to be mounted. Then the plate was spray painted black and everything got screwed on. In fig. 15 the controller circuit board is shown mounted by $1,5cm$ four standoffs. For wiring, ribbon cables were used to connect the switches and other input or output items. The sockets of the trigger and modules were wired to the controller circuit by a 5-line telephone cable[14] with shielding. This cable was also the choice for externally connecting the trigger and ignition modules to the controller.

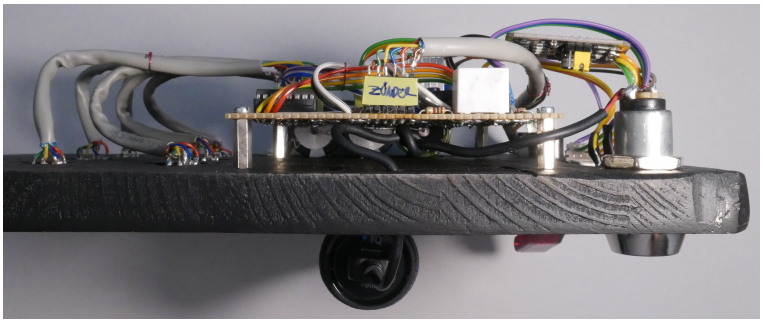


Figure 15: The circuit board depicted in fig. 13 mounted and wired on the backside of the devices interface viewed from the side.

[14] https://amzn.eu/d/65ZALnq

Figure 16: The gun case used for housing the controller.

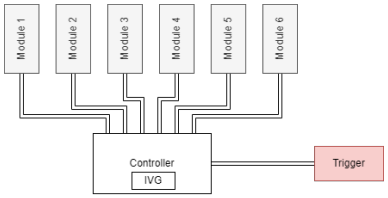
Source of fig. 16: `https://amzn.eu/d/eWSlyFs`

A gun case was bought of *Amazon* (See fig. 16), and the cushioning in the lower part of the case was removed, to make room for the controller. The complete controller/interface was put into a case and screwed in from the sides. Figure 17 depicts the finished controller powered on. The earlier mentioned lighting(See section 2.2.2 "Additional circuits") was installed in to top part of the case and the wires were hidden behind the cushioning. In fig. 17 the wires can be seen coming out from the top part of the case and going to the lower part(See fig. 17 right top corner).

Figure 17: The complete controller and interface inside its case.

1. ON/OFF key-switch
2. Status LED
3. Ignition voltage reached indicator (See section 2.1)
4. USB female socket for programming
5. Light ON/OFF switch
6. Controller arm switch
7. Trigger socket
8. Power bank
9. Module sockets

2.3 Trigger



The external trigger is responsible for starting the pyrotechnic show. Its purpose is to tell the controller when to start, but also tell the user what the state the controller is currently in. This is very important, because the user must be far away from the controller when the pyrotechnics are ignited, but also needs to be informed if the system is working properly or not.

2.3.1 Circuit

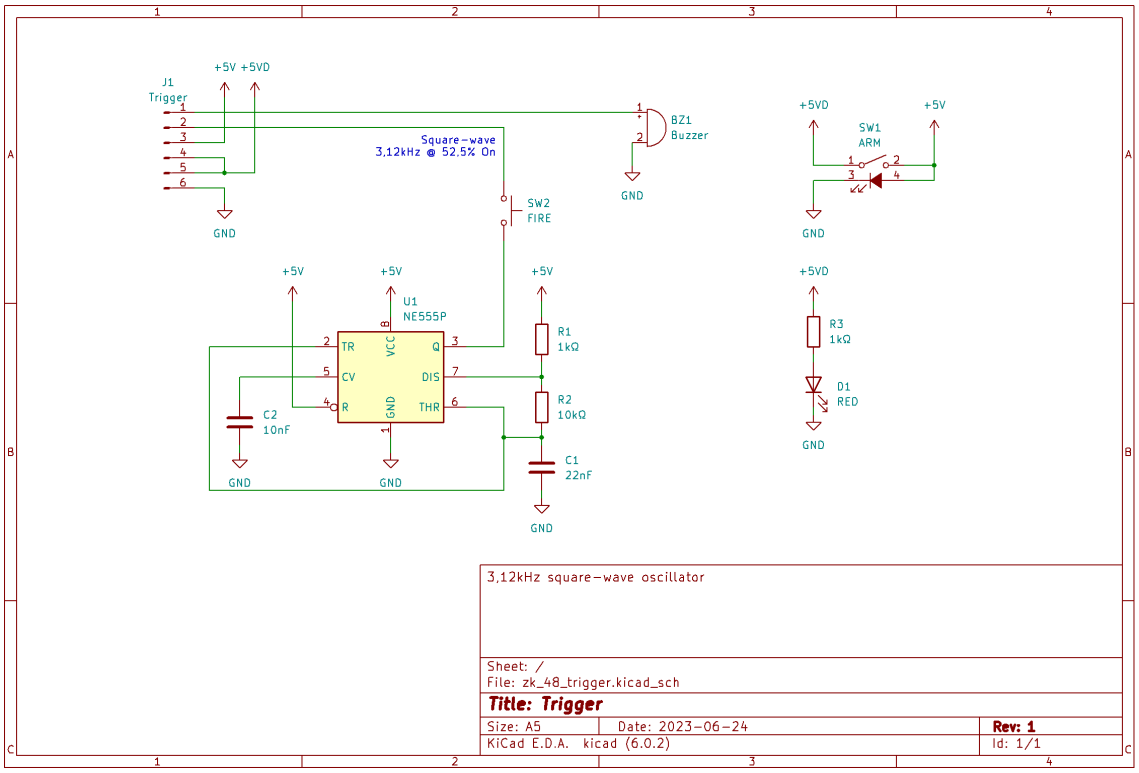


Figure 18: The circuit of the external trigger.

2.3.2 How does the trigger work?

The trigger receives one signal and sends three signals back to the controller. The first input signal is going to buzzer and is also connected to the buzzer on board the controller (See fig. 8). This buzzer gives the user feedback about the systems state, by changing the frequency of the sound produced. But more about the different sound and light outputs in section 3. One of the three outputs is the CONCD signal, which stands for "Connected" and tells the µC if the trigger is plugged in. This output is directly connected to the $+5V$ power line. The second output is the ARMED signal, which indicates to the µC if the trigger is armed. This signal is produced by toggling the arm switch $SW1$ which also turns on the NE555 oscillator. If the trigger is armed, the NE555 will generate a $3,12kHz$ square-wave signal with a $52,2\%$ on-time. This signal is not passed through, until the user holds down the fire $SW2$ button. Then the square-wave signal will be put through on the FIRE line of the trigger, therefore starting the firing sequence. A small LED $D1$ is also present on the trigger to indicate if the trigger has power.

2.3.3 Housing of the Trigger

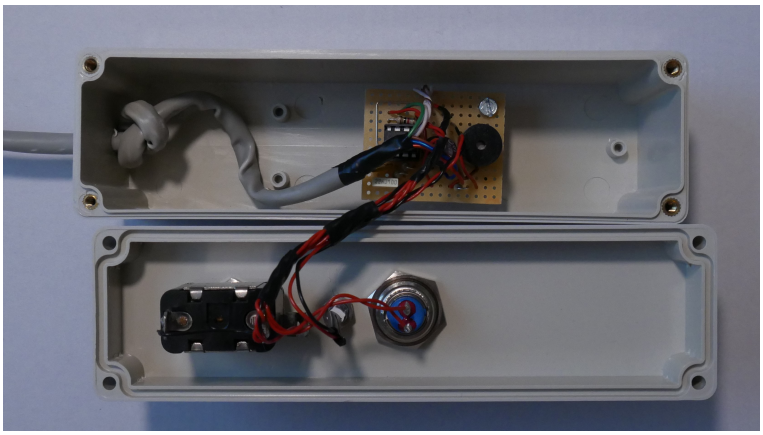


Figure 19: The external trigger circuit board mounted inside its case.

The circuit diagram of the trigger shown in fig. 8, got soldered onto a small perfboard. Together with the arm switch, power LED and fire button, the circuit was mounted into a ABS housing with the dimensions of $150x45x55mm$ as shown in fig. 19. The trigger uses a telephone cable, as described in section 2.2.5, with a length of approximately $15m$ to connect to the controller. In fig. 20 the finished controller is visible with the cable and plug.

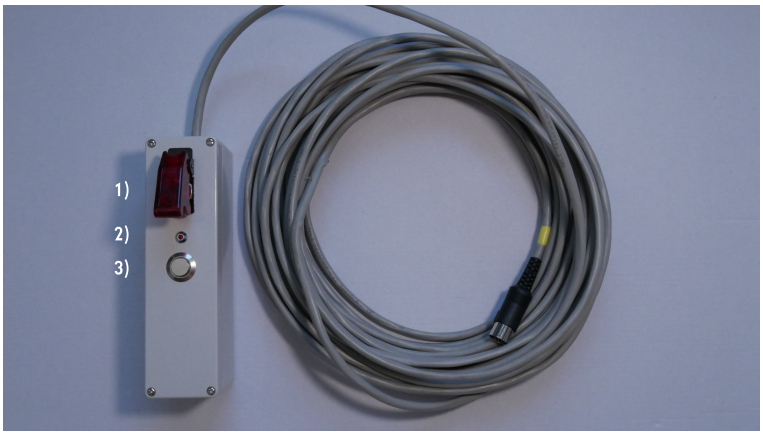
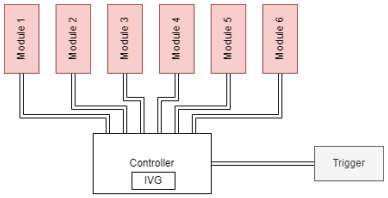


Figure 20: The external trigger with its cable.

1. Arm switch
2. Power LED
3. Fire button

2.4 Ignition Modules



The ignition modules are responsible for the ignition of the pyrotechnic bridge wire detonators and therefore carry a large responsibility. There is no margin of error, as the whole system depends on the ignition modules proper function. Also the cost of each ignition module must be considered, as six modules need to be build.

2.4.1 Circuit

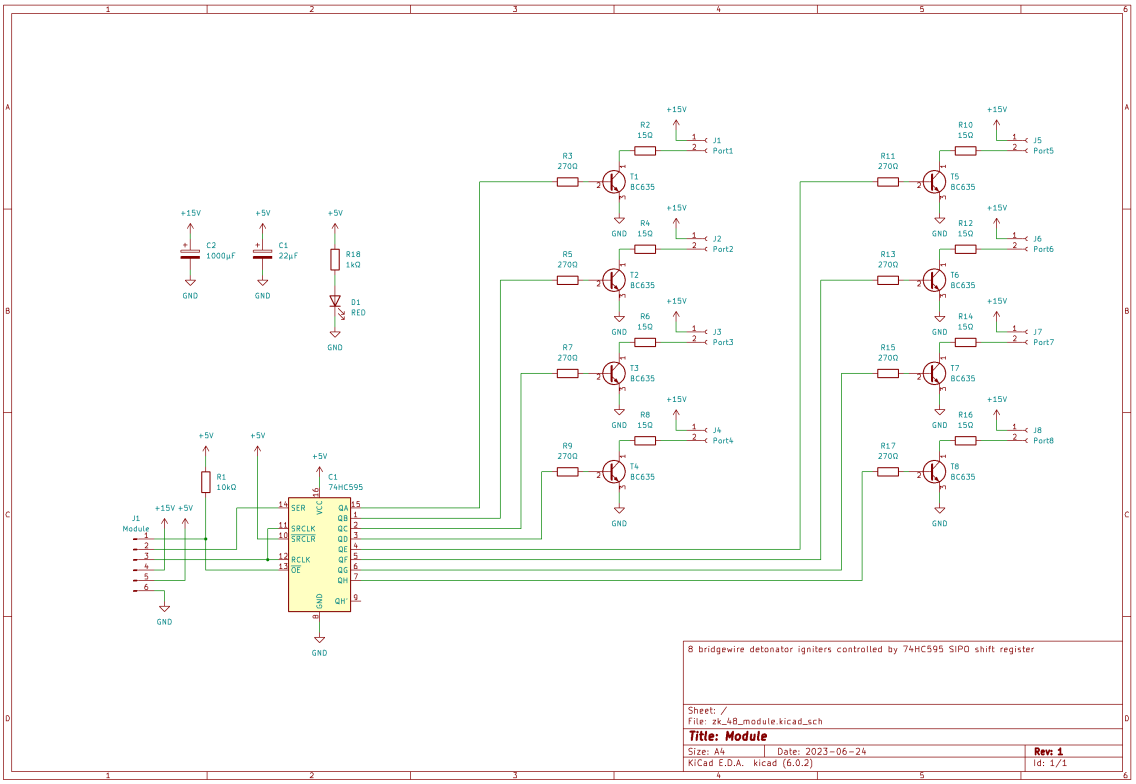


Figure 21: The circuit of the ignition module.

2.4.2 How does the Ignition Module work?

2.4.2.1 Ignition Circuit

When setting off a bridge wire detonator, a current larger than $500mA$ must flow, for guaranteed ignition. The switching transistor must therefore be able to handle such currents repeatedly without being damaged. Furthermore, considering that detonators can be faulty, for example have an internal short-circuit, those larger currents should also not destroy the transistor. Additional to the actual electrical requirements, the cost of each module should stay on the lower end, as six modules are going to be build with eight ignition circuits.

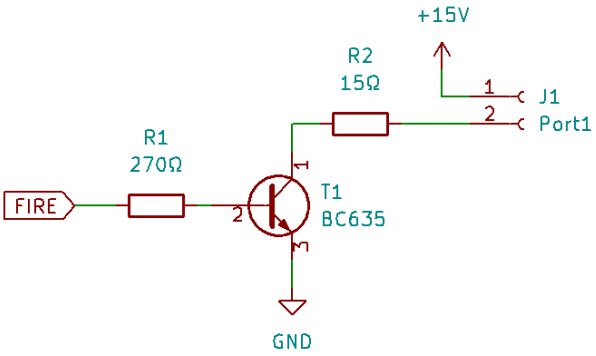


Figure 22: The circuit designed for setting off one bridge wire detonator inside the ignition module.

All aforementioned considerations were dealt by limiting the current through the transistor. Limiting the current was accomplished by using a 15Ω resistor after the bridge wire detonator (See fig. 22 $R2$) which limits the current, at $15V$ ignition voltage, to maximal $1A$. Knowing the maximal current and considering the other requirements, the NPN transistor BC635[15] in a TO-92 package, was chosen as the switching transistor. Its continuous collector current is equal to $1A$ and a costs 0,09€ per piece. To drive the BC635 a 270Ω resistor was used to limit the base current to circa $16mA$ (See eq. (2)), which results in the saturation of the transistor. Figure 22 displays the complete ignition circuit.

$$I_B = \frac{U_{IC,OUT} - U_{BE}}{R} = \frac{5V - 0,7V}{270\Omega} = 15,93mA \tag{2}$$

Designing this circuit also required selecting the proper ignition voltage level. The reason why the ignition voltage is $15V$ and not $5V$, which would make things much simpler, can be explained by Ohm's law: If the ignition voltage is $5V$ instead of $15V$ and the current is still gets limited to $1A$ by a 5Ω resistor, a reduction of the current through the detonator will occur. The calculations below (Equation (3) and eq. (4)) calculate the current for both cases, by simulating a bridge wire detonator with the same resistor value of $4,7\Omega$ as used in section 2.1.3.

$$I = \frac{U_{IG}}{R_2 + R_{BWD}} = \frac{15V}{15\Omega + 4,7\Omega} = 761,14mA \tag{3}$$

$$I = \frac{U_{IG}}{R_2 + R_{BWD}} = \frac{5V}{5\Omega + 4,7\Omega} = 515,54mA \tag{4}$$

Comparing result of eq. (3) to result of eq. (4), a strong drop in current is noticeable. This is a problem that worsens with additional detonators connected. In a typical pyrotechnic show it is not unlikely for three or more detonators to be connected in series(Parallel wiring is not recommend in general). A stronger transistor could be used, but this would raise cost, which is unwanted as 48 transistors are required.

[15] https://www.tme.eu/Document/aa873a3a455ba8f13e3474bd76bcc1d9/BC635_40.pdf

2.4.2.2 Controlling the Ignition Circuits

As mentioned in previous sections, the modules are based on a 8-Bit SIPO (Serial-in Parallel-out) shift register 74HC595[16].

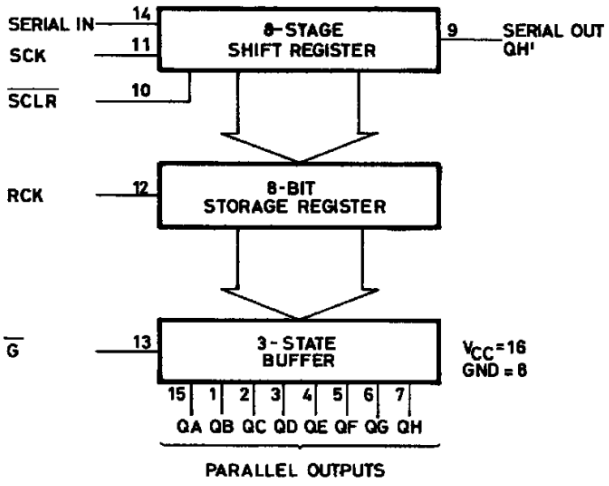


Figure 23: Functional diagram of the 74HC595

Source of fig. 23: `https://cdn-reichelt.de/documents/datenblatt/A240/74HC595%23STM.pdf`

The 74HC595 is made up of three subcomponents: the shift register, a register and a tri-state buffer(See fig. 23). To fire a port, the µC sends a byte mask serially to the shift-register (In fig. 23 see pin 14 SERIALIN and 11 SCK) where only one bit is set, indicating which port is being fired. Because the register clock RCK and shift register clock SCK are wired together (See fig. 21) the register will take on the values from the shift register. As also mentioned in section 2.2.2 "Peripheral Managing and Controlling Logic" the µC afterwards selects the correct module being fired by pulling low of the enable pin on the tri-state buffer (pin 13 in fig. 23), thus outputting the stored bit mask of the register onto the parallel outputs. Figure 21 shows that each output is directly connected to one ignition circuit, whereby the setting of an output to logic high fires a detonator.

2.4.2.3 Additional circuits

To reduce the large ignition currents through the cable which could cause interference in the signal lines, a large $1000\mu F$ capacitor C_2 was added to the $15V$ ignition voltage line inside the ignition module (See fig. 21). As charge would be stored closer to detonator theoretically this should in theory reduce peak currents, however this is speculative and the capacitor might not be needed at all.

[16] `https://www.ti.com/lit/ds/symlink/sn74hc595.pdf`

2.4.3 Housing of the Ignition Modules

The circuit got soldered onto a perfboard and for the housing a common electrical junction box, from the hardware store, was used as it is cheap, light weight, easy to cut and can be screwed against something. For connecting to the controller, four pieces of $4m$ and four pieces of $8m$ telephone cables were cut to size and soldered to the each of the eight modules circuit boards as seen in fig. 25. Also visible in fig. 25 is the orange stabilizing $1000\mu F$ capacitor $C2$ seen in fig. 21.

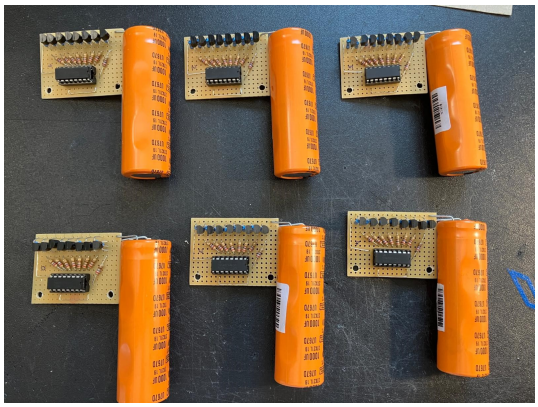


Figure 24: All six ignition modules soldered onto perfboards.

To connect the bridge wire detonators to the circuit, speaker terminals were used. In ?? the bottom two terminal rows represent the eight ports and the top row are all $15V$. This design is less ideal, because for two ports there is only one $15V$ terminal hole, but due limited space on top the housing this was a necessary compromise.

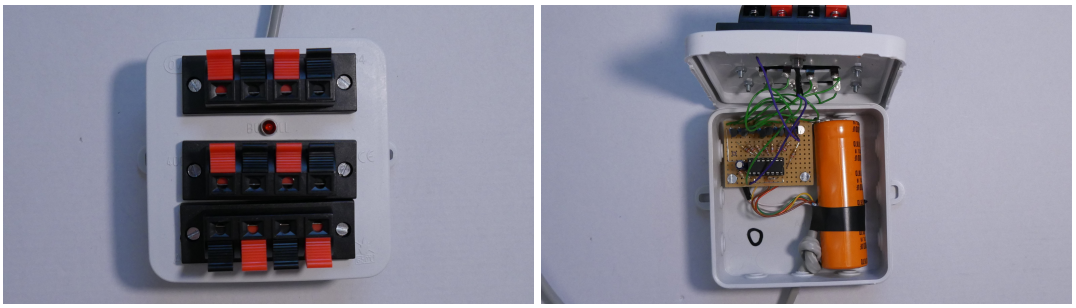


Figure 25: The ignition module from the inside (right) and the complete moudle with eight ports on the bottom and one power rail on the top (left).

3 Firmware

The Attiny861 is running a Firmware, based on a basic Moore state machine[17] with eight states. Each state performs an essential function, with distinct sound and status LED outputs. More about the state machine in section 3.4. The code was written in *C++*(Arduino *C++*) inside the Arduino IDE. Please note that the firing sequence, that controls the pyrotechnic show, is refereed to as program.

3.1 Pinout

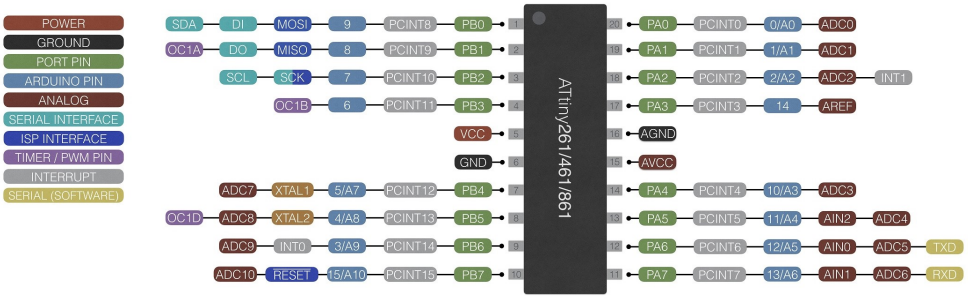


Figure 26: Pinout of the Attiny861 µC.

Source of fig. 26: `https://github.com/SpenceKonde/ATTinyCore`

All pins, shown in Figure 26, of the µC were used except pin 18 as this is the reset pin. The pin descriptors, used inside the firmware, are listed in table 1.

Pin	Name	Type	Description
3	MODUL_DATA	OUT	Dataline for serial data transmission
4	MODUL_CLK	OUT	Clock signal for serial data transmission
2	TRIGGER_FIRE	INT	Receives the trigger signal from the trigger
0	TRIGGER_ARMED	IN	High if trigger is armed
1	TRIGGER_CONNECTED	IN	High if trigger is connected
8	TRIGADD_A0	OUT	Address line for selecting the ignition module
9	TRIGADD_A1	OUT	Address line for selecting the ignition modul
10	TRIGADD_1E	OUT	Enable line for selecting the ignition modul
11	TRIGADD_2E	OUT	Enable line for selecting the ignition modul
12	STATUS_RED	OUT	Turns on the red status LED on the controller
13	STATUS_GREEN	OUT	Turns on the green status LED on the controller
12	STATUS_PIEP	OUT	Turns on the buzzer on controller and trigger
14	THIS_ARMED	IN	High if controller is armed
7	RX	IN	Receive signal for serial TTL communication
6	TX	OUT	Transmit signal for serial TTL communication

Table 1: Signal descriptions of all pins used of the Attiny861

[17] `https://en.wikipedia.org/wiki/Moore_machine`

3.2 Setup

The pinout listed in table 1 gets configured inside the *setup* function(See listing 1) which executes once on boot. Inside the same function call, the interrupt will be configured, to invoke a function called *fire*, if the pin voltage level changes from low to high on pin 2. Furthermore, the baud rate for the TTL serial communication is set to *57600*. More about the serial communication in section 3.5.

```
1  Serial.begin(BAUDRATE);
2
3  attachInterrupt(digitalPinToInterrupt(TRIGGER_FIRE), fire, RISING);
4
5  pinMode(MODUL_DATA, OUTPUT);
6  pinMode(MODUL_CLK, OUTPUT);
7  pinMode(TRIGADD_A0, OUTPUT);
8  pinMode(TRIGADD_A1, OUTPUT);
9  pinMode(TRIGADD_1E, OUTPUT);
10 pinMode(TRIGADD_2E, OUTPUT);
11 pinMode(STATUS_PIEP, OUTPUT);
12 pinMode(STATUS_RED, OUTPUT);
13 pinMode(STATUS_GREEN, OUTPUT);
14 pinMode(TRIGGER_FIRE, INPUT);
15 pinMode(TRIGGER_ARMED, INPUT);
16 pinMode(TRIGGER_CONNECTED, INPUT);
17 pinMode(THIS_ARMED, INPUT);
```

Listing 1: Code configuring the IO pins of the Attiny861.

All the register of the ignition modules are cleared during *setup*, by calling the *transmitData*(See section 3.3.2) function with an out of range index(See listing 2). This sets all ignition modules internal shift registers to 0. This is done due safety reasons, to prevent accidental premature firing, as already stated in section 2.2.2 "Arm safety circuit". For the same reason, the *setModule* function(See section 3.3.1) is used to disable all ignition modules. The program endpoint is also read from the internal EEPROM(More about that in Section 3.5).

```
1  transmitData(CLEAR_REG);
2  setModule(ALL_OFF);
3  pg_stop = readProgramEndpoint();
```

Listing 2: Code clearing and disabling ignition modules and reading the program endpoint.

The code snipped shown in Listing 3 is also executed in the setup function. Without this code in listing 3 the firmware would only execute at a eighth of normal speed. This means, a delay of $10ms$ takes $80ms$. This increase of the delay was measured, by programming the Attiny861 to output a $10ms$ pulse which got measured by a oscilloscope. The oscilloscope measured $80ms$ instead of $10ms$. Research led to a forum post where the code in listing 3 was found and subsequently tested, which proved to be successful in restoring the correct timing. Why this increase in delay occurs in the first place is unknown.

```
1  cli(); // Disable interrupts
2  CLKPR = (1<<CLKPCE); // Prescaler enable
3  CLKPR = 0x00; // Clock division factor
4  sei(); // Enable interrupts
```

Listing 3: Code for removing the clock division factor.

Source of the Code in listing 3: ***https://community.platformio.org/t/attiny-8mhz-wrong-timing\-in-delay-fastled-and-ne***
24992/3

3.3 Ignition of a Port

```
1  void ignite(byte module, byte port) //
2  {
3    transmitData(port);
4    setModule(module+1); // +1 because 0 (ALL_OFF) is turning off all modules
5
6    delay(IGNITION_TIME);
7
8    setModule(ALL_OFF);
9    transmitData(CLEAR_REG); // clear registers for safety reasons
10 }
```

Listing 4: Ignition function for setting of a bridge wire detonator given a port index and ignition module

The function *ignite*, shown in listing 4, will set of a bridge wire detonator by the principle explained in section 2.4.2 "Controlling the Ignition Circuits". On line 3 in listing 4 the port gets set on all ignition modules and on line 4 the correct ignition modules gets selected, thereby firing the port. After a delay called the ignition time, which is the time current runs through the detonator, all modules get unselected and the ignition modules registers are cleared.

3.3.1 Ignition Module addressing

```
1  #define nA1 0
2  #define nA0 1
3  #define E1 2
4  #define E2 3
5
6  // !! do not change !!
7  #define ALL_OFF 0
8  #define CLEAR_REG 10
9  //nA1 nA0,1E 2E
10 const byte module_resolve[7][4]=
11 {
12   {0,0,1,1},//ALL_OFF
13   {0,0,0,1},
14   {1,0,0,1},
15   {0,1,0,1},
16   {1,1,0,1},
17   {1,1,1,0},
18   {0,1,1,0}
19 };
```

Listing 5: Bit array for controlling the DMUX

A two dimensional byte array, behaving like lookup table, is used for controlling the two DMUX onboard the controller, which addresses the ignition modules. Every row of the constant *module_resolve* contains a unique bit pattern for each module. The values are the result of the wiring of the DMUX shown in section 2.2.1. This lookup table like design allows the ignition modules to be addressed by just a single integer value. Line 2 till 5 in listing 5 define aliases for mapping the column in *module_resolve* (as shown in line 10) onto the correct outputs *TRIGADD_A0*, *TRIGADD_A1*, *TRIGADD_E1* and *TRIGADD_E2*.

```
1  void setModule(byte module) //
2  {
3    digitalWrite(TRIGADD_A0, module_resolve[module][nA0]);
4    digitalWrite(TRIGADD_A1, module_resolve[module][nA1]);
5    digitalWrite(TRIGADD_1E, module_resolve[module][E1]);
6    digitalWrite(TRIGADD_2E, module_resolve[module][E2]);
7  }
```

Listing 6: Code selecting a module by its index

The function *setModule* in listing 6 receives a byte, which represents the index of the ignition module, by which the correct row in the *module_resolve* array gets indexed, to set the address and enable lines on the DMUX to enable the correct module.

3.3.2 Serial Data Transmission

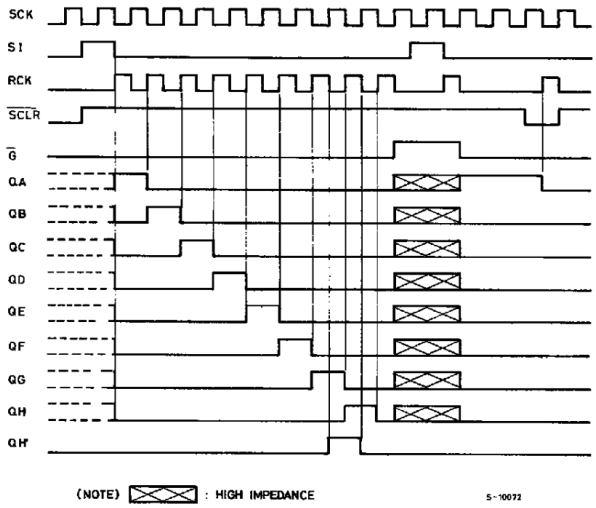


Figure 27: Timing diagram of the 74HC595.

Source of fig. 27: ***https://cdn-reichelt.de/documents/datenblatt/A240/74HC595%23STM.pdf***

As explained in section 2.4.2 "Controlling the Ignition Circuits" the ignition modules get the information, about what port to fire, over a serial data transmission. The timing diagram in fig. 27 shows how a bit gets shifted though the shift register and outputted by the outputs. This is also the same working principle of the port setting process. However when firing a port, the enable pin(Pin G in fig. 27) of the tri-sate buffer is turned off during the transmission and will only be enabled for $10ms$ after the transmission ended(the ignition time), to fire the set port.

```
1  void transmitData(byte port) //
2  {
3
4    for(byte port_index = 0; port_index < 9; port_index ++ )
5    {
6      if(port_index == port)
7      {
8        digitalWrite(MODUL_DATA,HIGH);
9      }else{
10       digitalWrite(MODUL_DATA,LOW);
11     }
12     delayMicroseconds(TRANSMISSION_SPEED);
13     digitalWrite(MODUL_CLK,HIGH);
14     delayMicroseconds(TRANSMISSION_SPEED);
15     digitalWrite(MODUL_CLK,LOW);
16     digitalWrite(MODUL_DATA,LOW);
17   }
```

Listing 7: Function for transmitting the port to the ignition modules

The function *transmitData* displayed in listing 7 sets the port on all ignition modules. Line 12 till 15 generate a nine impulses long clock signal with a $5\mu s$ on- and offtime. The reason for nine impulses instead of eight can be explained by viewing fig. 27. In this timing diagram the shift register clock *SCK* and the register clock *RCK* are 180 Degrees phase shifted, but in fig. 21 *RCK* and *SCK* are connected together. This means both the shift register clock and register clock receive the clock impulse at the same time. Thus an additional impulse is needed to fully push through the bit, as the register will always be one clock cycle behind. Lines 6 till 10 in Listing 7 are setting the data line to high, when the set port is equal to the port. This places the bit in the correct position, to create the desired bit pattern at the shift registers output.

3.4 State Machine

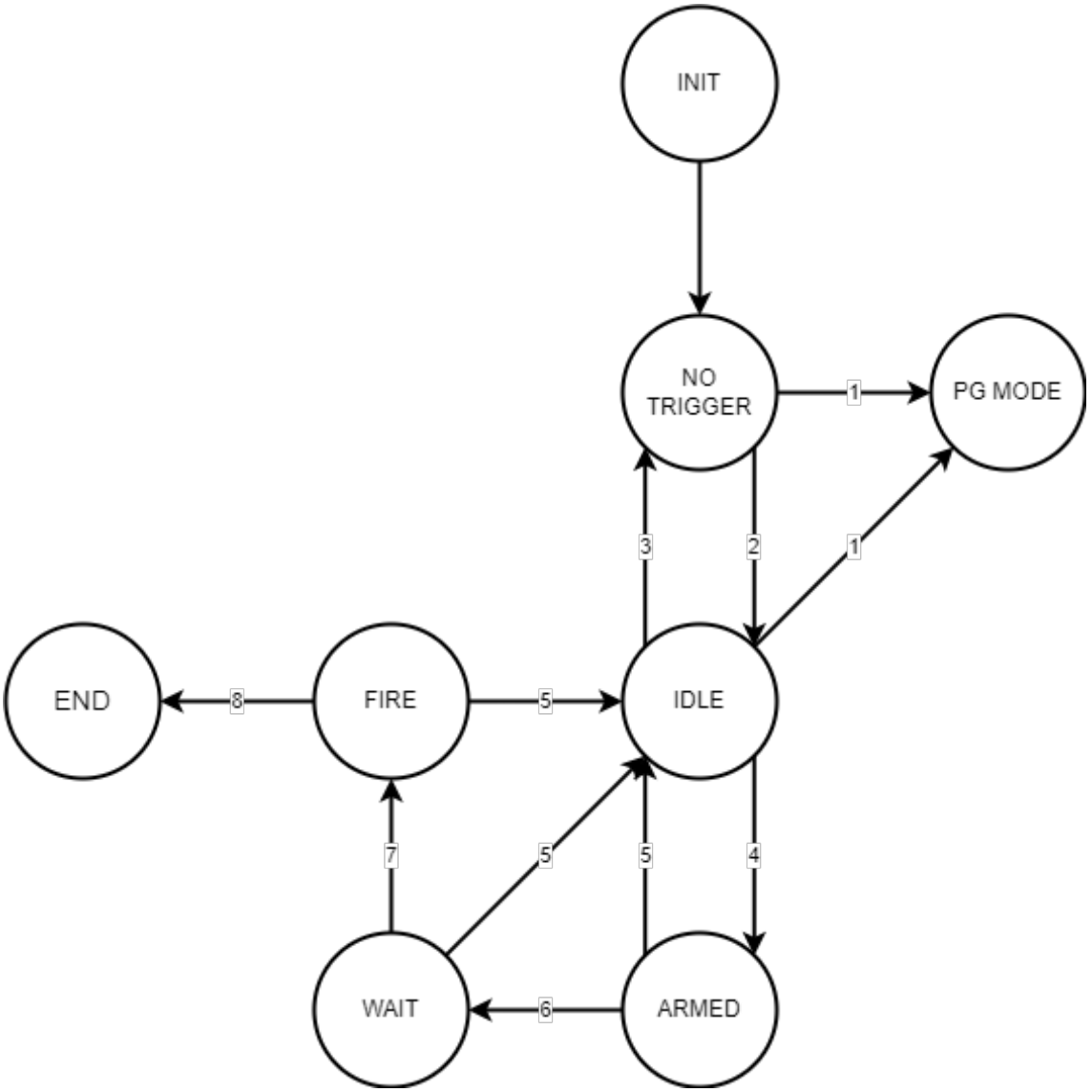


Figure 28: State diagram of the realised state machine.

The firmware starts at INIT and immediately enters NO_TRIGGER. If no trigger is connected to the controller, the system stays in NO_TRIGGER until the program mode gets called over USB, or until a trigger is connected. In state IDLE, the systems waits for both arm switches to be armed. If both are armed, the system transitions into ARMED. When in state ARMED, the system waits until it receives a fire signal from the trigger, therefore transitioning to state WAIT. In WAIT, the system stays for $10s$ afterwards it transitions to state FIRE, thus playing through the firing sequence as programmed in EEPROM. When the end is reached, state END is entered and stays there until the device is restarted. If during state FIRE, WAIT or ARMED the controller or the trigger gets unarmed the system returns to state IDLE. This state machine is depicted in fig. 28 together with the transition conditions in table 3 and the LED and buzzer output for each state in table 2.

State	Green	Red	Buzzer	Ontime
PG_MODE	1	1	0	-
INIT (3x)	1	1	1	100ms
	0	0	0	100ms
NO_TRIGGER	1	0	0	250ms
	0	1	0	250ms
IDLE	1	0	0	100ms
	0	0	0	500ms
ARMED	0	1	0	100ms
	0	0	0	500ms
WAIT	0	1	1	50ms
	0	0	0	50ms
FIRE	0	1	1	10ms (IGNITION_TIME)
	1	0	0	{PROGRAM[PG_INDEX].DELAY}ms
END	0	1	0	-

Table 2: Truth table for the state depended LED and buzzer outputs with timing information.

Nr	PG	TF	TA	TC	CA	WT	DN
1	1	X	X	X	X	X	X
2	X	X	0	1	0	X	X
3	X	X	X	0	X	X	X
4	X	X	1	1	1	X	X
5	X	X	0	X	X	X	X
5	X	X	X	X	0	X	X
6	X	1	1	1	1	1	X
7	X	X	1	1	1	0	X
8	X	X	X	X	X	X	1

Table 3: Truth table for the transition condition based on the state variables. ("X" = Don't care)

3.4.1 State Variables

State Variable	SV	Condition
Program Mode	PG	checkPGM()
Trigger Fire	TF	fire_pulse_counter >= FIRE_PULSE_SETOFF
Done	DN	pg_index == pg_stop
Wait	WT	wait_counter <= FIRE_DELAY
Trigger Armed	TA	digitalRead(TRIGGER_ARMED)
Trigger Connected	TC	digitalRead(TRIGGER_CONNECTED)
Controller Armed	CA	digitalRead(THIS_ARMED)

Table 4: List of all state variables and their conditions

The state variables listed in table 4 govern the behaviour of the state machine, as listed in table 3. Some state variables are directly read from the IO pins of the Attiny861 and others are the result of internal counter values. In the following paragraphs the state variables will be explained, with the exception of TA, TC and CA as they are generated externally(Please see fig. 8 in section 2.2).

3.4.1.1 PG (Program Mode)

The program mode state variable is set by a function called *checkPGM()*, which checks if a special keyword is received over USB. In listing 8 the code for checking the keyword is depicted.

```
1  char checkPGM()
2  {
3    if (Serial.available() > 0)
4    {
5      String str_buffer = Serial.readString();
6
7      if(str_buffer.compareTo("#pgm:")==0)
8      {
9        return true;
10     }
11   }
12   return false;
13 }
```

Listing 8: Checking if the keyword for entering the program mode is received.

The function listed in listing 8 reads from the serial(Line 3) stream coming from a external PC and then checks if the string is equal to the keyword(Line 7). The '#' and ':' are only included due consistency of all instructions. More about the syntax and the instructions in section 3.5.4.

3.4.1.2 TF (Trigger Fire)

To safely detect when the system should fire i.e go into state WAIT, the trigger has to send more than 1000 pulses in under 600ms to pin 2 of the Attiny861. Inside the setup function, depicted in section 3.2, the pin 2 (alias TRIGGER_FIRE) gets handled by an interrupt, which on signal change, invokes a function called *fire()*. This function is visible in listing 9.

```
1  void fire()
2  {
3    fire_pulse_counter++;
4  }
```

Listing 9: Interrupt function for handling the fire signal.

This *fire()* function counts up a variable called *fire_pulse_counter*, whereby the value is representing the number of pulses counted. If this counter reaches a value higher than 1000, the TF state variable takes on 1(See table 4). Directly after the comparison *fire_pulse_counter* must be set to 0, which is shown in listing 15 in line 5, which happens 600ms after the last comparison.

3.4.1.3 DN (Done)

The state variable DN is also the results of the comparison of an up counter and a constant. In section 3.2 listing 2 line 3, the program endpoint is read and saved into a variable called *pg_stop*. This constant stands for the number of steps in the pyrotechnic show. To go through each step of the pyrotechnic show, an up counter is used, incrementing after each firing step is complete. This will be explained in section 3.4.2 "FIRE". That counter is called *pg_index* and increments every time state FIRE is called. To generate the state variable DN *pg_index* and *pg_stop* are compared if they are equal DN is 1.

3.4.1.4 WT (Wait)

To generate the state variable WT, also a counter is used. This counter, stored in variable *wait_counter*, counts up every time state WAIT is called. If a threshold called *FIRE_DELAY* is reached WT takes on logic 1. In listing 10 the definition of the *wait_counter* is visible. Because of the delay of the WAIT state, each call results of a wait time of 100ms. To generate a 10s delay before entering state FIRE, the state WAIT has to be called 100 times, as also explained in the comment in line 1 listing 10.

```
1  #define FIRE_DELAY 100 // 1 = 100ms 100 = 10s
2  byte wait_counter;
```

Listing 10: Definition of *wait_counter* and the threshold.

3.4.2 States

3.4.2.1 *PG_MODE*

When the program mode or short *PG_MODE*, is entered the µC sends a special message back to the PC, indicating that *PG_MODE* was entered successfully. The *PG_MODE* state consists of a infinite loop calling a function called *programmMode()*, which manages the programming of the pyrotechnic program. This function gets explained in section 3.5. In listing 11 the code of *PG_MODE* is visible.

```
1       Serial.println("!pgm:");
2       setLEDState(HIGH,HIGH,LOW);
3       while(1)
4       {
5         programmMode();
6       }
```

Listing 11: Code of the *PG_MODE* state.

3.4.2.2 *INIT*

INIT is entered only once on boot and serves as a visual proof for the user, that the system is booting. Its purpose is to check if all output elements, like the buzzer, red and green LED's are working properly. As visible in table 2, all signals will be turned on and off three times, therefore making potential damage to the output elements visible. In listing 12 line 1 and 2 the jump conditions are visible.

```
1       if(PG == 0)new_state = STATE_NO_TRIGGER;
2       else if(CA == 0 && TC == 1 && TA == 0)new_state = STATE_IDLE;
3
4       for(int i = 0;i<3;i++){
5         setLEDState(HIGH,HIGH,HIGH);
6         delay(100);
7         setLEDState(LOW,LOW,LOW);
8         delay(100);
9       }
```

Listing 12: Code of the *INIT* state.

3.4.2.3 *NO_TRIGGER*

The state *NO_TRIGGER* is a major safety features which prevents the system to from directly jumping into the *ARMED* state. When the system is booting and the user forgot to disable the arm switches, the system is prevented to directly jump into the *ARMED* state. This is accomplished by requiring the user to dearm the system before state *IDLE* even can be entered(See Table 3 Nr. 2 and 3). It not only acts as a safety feature, but also indicates to the user that no trigger is connected, where also the name of the state originated as the safety feature was added later during development.

```
1       if(PG == 1)new_state = STATE_PG_MODE;
2       else if(CA == 0 && TC == 1 && TA == 0)new_state = STATE_IDLE;
3
4       setLEDState(HIGH,LOW,LOW);
5       delay(250);
6       setLEDState(LOW,HIGH,LOW);
7       delay(250);
8       break;
```

Listing 13: Code of the *NO_TRIGGER* state.

3.4.2.4 *IDLE*

In state *IDLE* the system waits for the user to arm it. Its the return point, if during any further operation the system gets dearmed. Also in *NO_TRIGGER* and *IDLE* the user can enter the program mode via USB. In Listing 14 in line 5 the *wait_counter* gets reset thus always needing 10*s* to enter state *FIRE* from state *WAIT*.

```
1  if(PG == 1)new_state = STATE_PG_MODE;
2  else if(TC == 0)  new_state = STATE_NO_TRIGGER;
3  else if(CA == 1 && TA == 1)  new_state = STATE_ARMED;
4
5  wait_counter = 0;
6
7  setLEDState(HIGH,LOW,LOW);
8  delay(100);
9  setLEDState(LOW,LOW,LOW);
10 delay(500);
```

Listing 14: Code of the *IDLE* state.

3.4.2.5 *ARMED*

When both arm switches are turned on, the system will transition to state *ARMED*. This state will indicate use the buzzer to notify that the device is armed and ready for operation. If the fire signal is sent and 1000 pulses are counted in under 600*ms* the state *WAIT* is entered (See Listing 15).

```
1  if(TA == 0)new_state = STATE_IDLE;
2  else if(CA == 0)new_state = STATE_IDLE;
3  if(TF == 1)new_state = STATE_WAIT;
4
5  fire_pulse_counter = 0;
6
7  setLEDState(LOW,HIGH,HIGH);
8  delay(100);
9  setLEDState(LOW,LOW,LOW);
```

Listing 15: Code of the *ARMED* state.

3.4.2.6 *WAIT*

In *WAIT* the system will wait for 10*s* whilst using the buzzer to warn the user of the upcoming start of the pyrotechnic show, when finally transitioning to *FIRE*. In Listing 16 in line 5 the *wait_counter* gets incremented.

```
1  if(TA == 0)new_state = STATE_IDLE;
2  else if(TA == 0)new_state = STATE_IDLE;
3  else if  (WT == 0)  new_state = STATE_FIRE;
4
5  wait_counter++;
6
7  setLEDState(LOW,HIGH,HIGH);
8  delay(50);
9  setLEDState(LOW,LOW,LOW);
10 delay(50);
```

Listing 16: Code of the *WAIT* state.

3.4.2.7 *FIRE*

When the *wait_counter* has reached its final value the system transitions into *FIRE* prompting the start of the show. In **??** in line 5 the program gets executed by reading in the next port,module and delay to fire and after waiting the read delay firing the next bridge wire detonate in line 10. Afterwards the program counter or *pg_index* gets incremented to fire the next pyrotechnic effect in the program. This process continues until the program endpoint is reached, as indicated by the DN state variable.

```
1   if(TA == 0)new_state = STATE_IDLE;
2   else if(TA == 0)new_state = STATE_IDLE;
3   else if(DN == 1)  new_state = STATE_END;
4
5   section pgpoint = readProgramPoint(pg_index);
6
7   setLEDState(HIGH,LOW,LOW);
8   delay(pgpoint.msdelay);
9   setLEDState(LOW,HIGH,HIGH);
10  ignite(pgpoint.module,pgpoint.port);
11
12  pg_index++;
```

Listing 17: Code of the *FIRE* state.

3.4.2.8 *END*

The *END* state is the end of the program and will stay stuck in this state until the system gets turned off. It also serves as a safety feature as the system is unable to fire any more, thus making it safe for the user to approach the device after the show has ended.

3.5 Program Mode

The program mode is entered by sending the command "#PGM:" (See Section 3.4.1 "PG (Program Mode)") over USB, when the system is in state *IDLE* or *NO_TRIGGER*. As explained in Section 3.4.2 "PG_MODE", when entering the program mode, the system runs a infinite loop, calling the function *programmMode()* which breaks down a command comming over serial. This is accomplished in three steps: Reading data from Serial, break the command apart and then interpret the broken down command.

```
1 if (Serial.available() > 0)
2 {
3   String str_buffer = Serial.readString();
4   delay(1);
```

Listing 18: Reading data from serial.

To read data over USB a the function *readString()* is used. This function returns a string containing the content of the serial buffer. Before reading from this buffer, it is necessary to check if data is available, which is done by the function *available()*. On line 4 in Listing 18 a delay with one millisecond is used to slow down the loop as no other delay is present. As TTL serial communication is half duplex, meaning sending and receiving data at the same time is not possible, therefore the delay is preventing a error that sometimes occurs, when reading data and directly afterwards sending data.

```
1   char split_index[PGM_MAXARGS];
2   split_index[0] = str_buffer.indexOf(PGM_START_CHAR);
3   for(int index = 1; index < PGM_MAXARGS; index++)
4   {
5     split_index[index] = str_buffer.indexOf(
6       PGM_ARG_CHAR,
7       split_index[index-1]+1);
8   }
9
10  String cmd = str_buffer.substring(split_index[0]+1, split_index[1]);
```

Listing 19: Break down the command in its parts.

The next step is to break down the command. For the complete instruction set please read in Section 3.5.4. A command has always the same structure:

#[CMD-NAME]:[ARG-1]:[ARG-2]:[ARG-3]:[ARG-4]:

The hashtag at the beginning of the command indicates the start of the command while the colons separate the arguments. To read the command name and arguments, first the indices of the hashtag and colons are determined by using the *indexOf* method (See Listing 19 line 5). This function returns the index of the first char being searched for, starting the search at the entered offset. In this case, the last found index is the offset for the next search(See Listing 19 line 7). The found indices are stored in any array for later use. To get the command name as its own string, the *substring* function is utilized, which cuts out a string, given a start index and stop index (See line 10).

```
1   if(cmd == cmd_list)
```

Listing 20: Checking if the received command is the *list* command.

The command can now be interpreted by having a if-statement, for each command, checking for equality (For an example see Listing 20). If the received command is equal to one of the commands listed in Section 3.5.4, its corresponding code is executed.

3.5.1 *list*

The *list* command outputs the entire internally stored pyrotechnic show as a list of all steps including the program stop index. This helps the user to check if the pyrotechnic show is programmed correctly or to just see the program itself. The implementation is shown in Listing 21.

```
1   Serial.println("!list:");
2   Serial.print(PGM_ANS_CHAR);
3   Serial.print("stop:");
4   Serial.print(pg_stop);
5   Serial.println(PGM_ARG_CHAR);
6
7   for(int index=0; index < PG_LENGTH; index++)
8   {
9     section pgpoint = readProgramPoint(index);
10    Serial.print(PGM_ANS_CHAR);
11    Serial.print("set:");
12    Serial.print(index);
13    Serial.print(PGM_ARG_CHAR);
14    Serial.print(pgpoint.module);
15    Serial.print(PGM_ARG_CHAR);
16    Serial.print(pgpoint.port);
17    Serial.print(PGM_ARG_CHAR);
18    Serial.print(pgpoint.msdelay);
19    Serial.println(PGM_ARG_CHAR);
20  }
```

Listing 21: Implementation of the *list* command.

3.5.2 *set*

For actually programming the pyrotechnic show, the user uses the *set* command. This command takes in four arguments which are all cut out of the buffer (See Listing 22 line 1-3, 7-9, 11-13, 15-17) by the function *substring* with the indices determined earlier and then stored temporarily in a *section* struct. Finally the struct gets stored in the internal EEPROM (Line 19).

```
1   byte index = str_buffer.substring(
2     split_index[1]+1,
3     split_index[2]).toInt();
4
5   section new_pgpoint;
6
7   new_pgpoint.msdelay = (unsigned short)str_buffer.substring(
8     split_index[4]+1,
9     split_index[5]).toInt();
10
11  new_pgpoint.port = (byte)str_buffer.substring(
12    split_index[3]+1,
13    split_index[4]).toInt();
14
15  new_pgpoint.module = (byte)str_buffer.substring(
16    split_index[2]+1,
17    split_index[3]).toInt();
18
19  writeProgramPoint(index,new_pgpoint);
20
21  Serial.println("!set:");
```

Listing 22: Implementation of the *set* command.

3.5.3 *stop*

To set the program endpoint alias *pg_stop*, the *stop* command is used. *stop* has one argument, representing the stop index. This argument converted to an usable integer, by first cutting out the value as a string with the *substring* function (See Listing 23 line 1) and then parsing it. The resulting value is then directly written into the internal EEPROM.

```
1        pg_stop = str_buffer.substring(split_index[1]+1,split_index[2]).toInt();
2
3        writeProgramEndpoint(pg_stop);
4        Serial.println("!stop:");
```

Listing 23: Implementation of the *stop* command.

3.5.4 Instruction Set

Command	Description
#pgm:	Enters the program mode
#list:	Lists the stored pyrotechnic program
#set:[INDEX]:[MODULE]:[PORT]:[DELAY]:	Sets a point in the pyrotechnic program
#stop:[STOP_INDEX]:	Sets the end of the pyrotechnic program

Table 5: List of all commands

4 Appendix

4.1 Pricing

Name	Amount	Price (EUR)	Total (EUR)
Transistors	48	0.09	4.32
Resistors	105	0.012	1.26
Resistors 15Ohm	48	0.05	2.42
Buzzer	2	1.00	2.00
Perfboard	2	2.725	5.45
Speaker Terminal	18	0.404	7.272
MAB 5 (Plug)	7	0.72	5.04
MAS 50 (Socket)	7	0.675	4.725
74HC595	6	0.313	1.878
74LS139	1	0.81	0.81
Attiny 861	1	2.42	2.42
UART-To-TTL Converter	1	4.02	4.02
Solder	1	12.02	12.02
Power Bank	1	20.16	20.16
Gun case	1	22.99	22.99
Ignition Module case	6	3.99	23.94
Telephone Cable	1	24.79	24.79
Trigger ABS housing	1	4.99	4.99
Cost for Buttons , Switches and LEDs (ca.)	1	10.00	10.00
Screws and Standoffs (ca.)	1	10.00	10.00
Capcaitors,Diodes,Relays, IC's and more (ca.)	1	15.00	15.00
			185.50

Table 6: All parts of the ZK-48 listed with prices. higher.

In Table 6, the cost of the complete system is split into all parts that make it up. Some values are estimates, as some parts were not bought specifically for this, instead were already on hand, which could result in a lower price or higher depending on the source. Not considering the many months of development a price of 185.50 Euro is comparatively low as the price range for similar systems(without programming capability) range from 400 Euro [18] to 700 Euro [19].

4.2 Conclusion

[18] https://www.firework-shop.de/Funkzuendanlage-48-Kanal-DBR01-X4-48::104404.html
[19] https://feuerwerkershop.de/produkt/funkzuendanlagen/sonstige-zuendanlagen/48-kanal-zuendanlage-db24-set/

4.3 Firmware Code

```
// Copyright: Markus K. 2023
// Github:    https://github.com/inimodo

#include <EEPROM.h>

#define MODUL_DATA 3
#define MODUL_CLK 4
#define TRIGGER_FIRE 2
#define TRIGGER_ARMED 0
#define TRIGGER_CONNECTED 1
#define TRIGADD_A0 8
#define TRIGADD_A1 9
#define TRIGADD_1E 10
#define TRIGADD_2E 11
#define STATUS_RED 12
#define STATUS_PIEP 5
#define STATUS_GREEN 13
#define THIS_ARMED 14
#define RX 7
#define TX 6

// pin mapping for selection of the module
//D11/A0 -> nA1
//D10/A1 -> nA0
//D9 /A2 -> 1E
//D8 /A3 -> 2E

// !! do not change !!
#define nA1 0
#define nA0 1
#define E1 2
#define E2 3

// !! do not change !!
#define ALL_OFF 0
#define CLEAR_REG 10
//nA1 nA0,1E 2E
const byte module_resolve[7][4]=
{
  {0,0,1,1},//ALL_OFF
  {0,0,0,1},
  {1,0,0,1},
  {0,1,0,1},
  {1,1,0,1},
  {1,1,1,0},
  {0,1,1,0}
};

typedef struct _section {
  byte module;
  byte port;
  unsigned short msdelay;
} section;

// the program length (number of ports) higher values do not make sense
#define PG_LENGTH 48
byte pg_stop = 0;
byte pg_index = 0;

```

```
60  // chars for program mode operation
61  #define PGM_ARG_CHAR ':'
62  #define PGM_START_CHAR '#'
63  #define PGM_ANS_CHAR '!'
64  #define PGM_MAXARGS 6
65
66  const char* cmd_set = "set";
67  const char* cmd_list = "list";
68  const char* cmd_stop = "stop";
69  const char* cmd_pgm = "pgm";
70
71  // threshold for the number of impules before starting the wait sequence
72  #define FIRE_PULSE_SETOFF 1000
73  short fire_pulse_counter = 0;
74  // delay before ignition of the program
75  #define FIRE_DELAY 100 // 1 = 100ms 100 = 10s
76  byte wait_counter;
77
78
79  // time each ignition pulse takes - depends on e-igniter
80  #define IGNITION_TIME 10 // ms
81  // clock speed of transmitData() !! do not change !!
82  #define TRANSMISSION_SPEED 5 //us
83
84  #define BAUDRATE 57600
85
86  #define STATE_END 8
87  #define STATE_WAIT 7
88  #define STATE_FIRE 6
89  #define STATE_ARMED 5
90  #define STATE_IDLE 4
91  #define STATE_NO_TRIGGER 3
92  #define STATE_INIT 2
93  #define STATE_PG_MODE 1
94
95  byte state = STATE_INIT;
96
97  // ################## // Setup // ################## //
98
99  void setup()
100 { //
101
102   // this is not my code!
103   // source: https://community.platformio.org/t/
104   //         attiny-8mhz-wrong-timing-in-delay-fastled-and-neopixel/24992/3
105   // start
106   cli(); // Disable interrupts
107   CLKPR = (1<<CLKPCE); // Prescaler enable
108   CLKPR = 0x00; // Clock division factor
109   sei(); // Enable interrupts
110   // end
111
112   Serial.begin(BAUDRATE);
113
114   attachInterrupt(digitalPinToInterrupt(TRIGGER_FIRE), fire, RISING);
115
116   pinMode(MODUL_DATA, OUTPUT);
117   pinMode(MODUL_CLK, OUTPUT);
118   pinMode(TRIGADD_A0, OUTPUT);
119   pinMode(TRIGADD_A1, OUTPUT);
120   pinMode(TRIGADD_1E, OUTPUT);
```

```
121   pinMode(TRIGADD_2E,OUTPUT);
122   pinMode(STATUS_PIEP,OUTPUT);
123   pinMode(STATUS_RED,OUTPUT);
124   pinMode(STATUS_GREEN,OUTPUT);
125   pinMode(TRIGGER_FIRE,INPUT);
126   pinMode(TRIGGER_ARMED,INPUT);
127   pinMode(TRIGGER_CONNECTED,INPUT);
128   pinMode(THIS_ARMED,INPUT);
129
130   transmitData(CLEAR_REG);
131   setModule(ALL_OFF);
132   pg_stop = readProgramEndpoint();
133
134 }
135
136 // ################## // EEPROM Functions // ################## //
137
138 void writeProgramEndpoint(byte endpoint)
139 {
140   EEPROM.write(0,endpoint);
141 }
142
143 byte readProgramEndpoint()
144 {
145   return EEPROM.read(0);
146 }
147
148 void writeProgramPoint(byte index,section pg_point)
149 {
150   short real_address = index*sizeof(section) + sizeof(byte);
151   EEPROM.put(real_address,pg_point);
152
153 }
154
155 section readProgramPoint(byte index)
156 {
157   section pg_point;
158   short real_address = index*sizeof(section) + sizeof(byte);
159   EEPROM.get(real_address,pg_point);
160   return pg_point;
161 }
162
163 // ################## // Program Mode // ################## //
164
165 // checks if program mode must be entered
166 char checkPGM()
167 {
168   if (Serial.available() > 0)
169   {
170     String str_buffer = Serial.readString();
171
172     if(str_buffer.compareTo("#pgm:")==0)
173     {
174       return true;
175     }
176   }
177   return false;
178 }
179
180 // programs the internal EEPROM via serial commands
181 byte programmMode()
```

```
182 {
183   if (Serial.available() > 0)
184   {
185     String str_buffer = Serial.readString();
186     delay(1);
187
188     char split_index[PGM_MAXARGS];
189     split_index[0] = str_buffer.indexOf(PGM_START_CHAR);
190     for(int index = 1; index < PGM_MAXARGS; index++)
191     {
192       split_index[index] = str_buffer.indexOf(
193         PGM_ARG_CHAR,
194         split_index[index-1]+1);
195     }
196
197     String cmd = str_buffer.substring(split_index[0]+1, split_index[1]);
198
199     if(cmd == cmd_list)
200     {
201       Serial.println("!list:");
202       Serial.print(PGM_ANS_CHAR);
203       Serial.print("stop:");
204       Serial.print(pg_stop);
205       Serial.println(PGM_ARG_CHAR);
206
207       for(int index=0; index < PG_LENGTH; index++)
208       {
209         section pgpoint = readProgramPoint(index);
210         Serial.print(PGM_ANS_CHAR);
211         Serial.print("set:");
212         Serial.print(index);
213         Serial.print(PGM_ARG_CHAR);
214         Serial.print(pgpoint.module);
215         Serial.print(PGM_ARG_CHAR);
216         Serial.print(pgpoint.port);
217         Serial.print(PGM_ARG_CHAR);
218         Serial.print(pgpoint.msdelay);
219         Serial.println(PGM_ARG_CHAR);
220       }
221       return;
222     }else if(cmd== cmd_stop)
223     {
224       pg_stop = str_buffer.substring(split_index[1]+1,split_index[2]).toInt();
225
226       writeProgramEndpoint(pg_stop);
227       Serial.println("!stop:");
228       return;
229     }else if(cmd== cmd_set)
230     {
231       byte index = str_buffer.substring(
232         split_index[1]+1,
233         split_index[2]).toInt();
234
235       section new_pgpoint;
236
237       new_pgpoint.msdelay = (unsigned short)str_buffer.substring(
238         split_index[4]+1,
239         split_index[5]).toInt();
240
241       new_pgpoint.port = (byte)str_buffer.substring(
242         split_index[3]+1,
```

```
243           split_index[4]).toInt();
244
245         new_pgpoint.module = (byte)str_buffer.substring(
246           split_index[2]+1,
247           split_index[3]).toInt();
248
249         writeProgramPoint(index,new_pgpoint);
250
251         Serial.println("!set:");
252         return;
253       }
254       Serial.println("!error:");
255     }
256   }
257
258   // ################## // IO Functions // ################## //
259
260   // sets the port on ALL modules
261   void transmitData(byte port) //
262   {
263
264     for(byte port_index = 0; port_index < 9; port_index ++ )
265     {
266       if(port_index == port)
267       {
268         digitalWrite(MODUL_DATA,HIGH);
269       }else{
270         digitalWrite(MODUL_DATA,LOW);
271       }
272       delayMicroseconds(TRANSMISSION_SPEED);
273       digitalWrite(MODUL_CLK,HIGH);
274       delayMicroseconds(TRANSMISSION_SPEED);
275       digitalWrite(MODUL_CLK,LOW);
276       digitalWrite(MODUL_DATA,LOW);
277     }
278   }
279
280   // selects what module is meant to ignite the set Port
281   void setModule(byte module) //
282   {
283     digitalWrite(TRIGADD_A0,module_resolve[module][nA0]);
284     digitalWrite(TRIGADD_A1,module_resolve[module][nA1]);
285     digitalWrite(TRIGADD_1E,module_resolve[module][E1]);
286     digitalWrite(TRIGADD_2E,module_resolve[module][E2]);
287   }
288
289   // ignites a port on a given module
290   void ignite(byte module, byte port) //
291   {
292     transmitData(port);
293     setModule(module+1); // +1 because 0 (ALL_OFF) is turning off all modules
294
295     delay(IGNITION_TIME);
296
297     setModule(ALL_OFF);
298     transmitData(CLEAR_REG); // clear registers for safety reasons
299   }
300
301   // sets status led
302   void setLEDState(byte G,byte R,byte P)
303   {
```

```
304   digitalWrite(STATUS_RED,R);
305   digitalWrite(STATUS_GREEN,G);
306   digitalWrite(STATUS_PIEP,P);
307 }
308
309 // ################# // State Machine // ################# //
310
311 // does what the name implies
312 byte FSM(byte state)
313 {
314   byte PG = checkPGM();
315   byte TF = fire_pulse_counter >= FIRE_PULSE_SETOFF;
316   byte DN = pg_index == pg_stop;
317   byte WT = wait_counter <= FIRE_DELAY;
318   byte TA = digitalRead(TRIGGER_ARMED);
319   byte TC = digitalRead(TRIGGER_CONNECTED);
320   byte CA = digitalRead(THIS_ARMED);
321
322   byte new_state = state;
323
324   switch(state)
325   {
326     case STATE_PG_MODE:
327       Serial.println("!pgm:");
328       setLEDState(HIGH,HIGH,LOW);
329       while(1)
330       {
331         programmMode();
332       }
333       break;
334
335     case STATE_INIT:
336       if(PG == 0)new_state = STATE_NO_TRIGGER;
337       else if(CA == 0 && TC == 1 && TA == 0)new_state = STATE_IDLE;
338
339       for(int i = 0;i<3;i++){
340         setLEDState(HIGH,HIGH,HIGH);
341         delay(100);
342         setLEDState(LOW,LOW,LOW);
343         delay(100);
344       }
345
346       break;
347
348     case STATE_NO_TRIGGER:
349       if(PG == 1)new_state = STATE_PG_MODE;
350       else if(CA == 0 && TC == 1 && TA == 0)new_state = STATE_IDLE;
351
352       setLEDState(HIGH,LOW,LOW);
353       delay(250);
354       setLEDState(LOW,HIGH,LOW);
355       delay(250);
356       break;
357
358     case STATE_IDLE:
359       if(PG == 1)new_state = STATE_PG_MODE;
360       else if(TC == 0)  new_state = STATE_NO_TRIGGER;
361       else if(CA == 1 && TA == 1)  new_state = STATE_ARMED;
362
363       wait_counter = 0;
364
```

```
365         setLEDState(HIGH,LOW,LOW);
366         delay(100);
367         setLEDState(LOW,LOW,LOW);
368         delay(500);
369         break;
370
371       case STATE_ARMED:
372         if(TA == 0)new_state = STATE_IDLE;
373         else if(CA == 0)new_state = STATE_IDLE;
374         if(TF == 1)new_state = STATE_WAIT;
375
376         fire_pulse_counter = 0;
377
378         setLEDState(LOW,HIGH,HIGH);
379         delay(100);
380         setLEDState(LOW,LOW,LOW);
381         delay(500);
382         break;
383
384       case STATE_WAIT:
385         if(TA == 0)new_state = STATE_IDLE;
386         else if(TA == 0)new_state = STATE_IDLE;
387         else if (WT == 0) new_state = STATE_FIRE;
388
389         wait_counter++;
390
391         setLEDState(LOW,HIGH,HIGH);
392         delay(50);
393         setLEDState(LOW,LOW,LOW);
394         delay(50);
395         break;
396
397       case STATE_FIRE:
398         if(TA == 0)new_state = STATE_IDLE;
399         else if(TA == 0)new_state = STATE_IDLE;
400         else if(DN == 1) new_state = STATE_END;
401
402         section pgpoint = readProgramPoint(pg_index);
403
404         setLEDState(HIGH,LOW,LOW);
405         delay(pgpoint.msdelay);
406         setLEDState(LOW,HIGH,HIGH);
407         ignite(pgpoint.module,pgpoint.port);
408
409         pg_index++;
410         break;
411
412       case STATE_END:
413         setLEDState(LOW,HIGH,LOW);
414         break;
415
416     }
417     return new_state;
418   }
419
420   // ################# // Main Loop // ################# //
421
422   void loop()
423   {
424     state = FSM(state);
425   }
```

```
426
427 void fire()
428 {
429   fire_pulse_counter++;
430 }
```

4.4 Recognitions

All circuits were drawn with the help of *KiCad* 6.0[20]

All flowcharts and diagrams were drawn with the help of *Drawio*[21]

[20] https://www.kicad.org/
[21] https://app.diagrams.net/