ZK
48

Technical Documentation

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

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Contents

1 Introduction

The ZK-48 (German "Zündkasten 48 Ausgänge") ignition system was developed because there are no affordable cheap programmable systems. The goal is 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. Although this should not be viewed as an instruction on how to build this device, but the author hopes it is useful anyway to a pyrotechnic and or electronics enthusiast. The finished device is shown in Figure 1 with the trigger on the right and one module on the left.

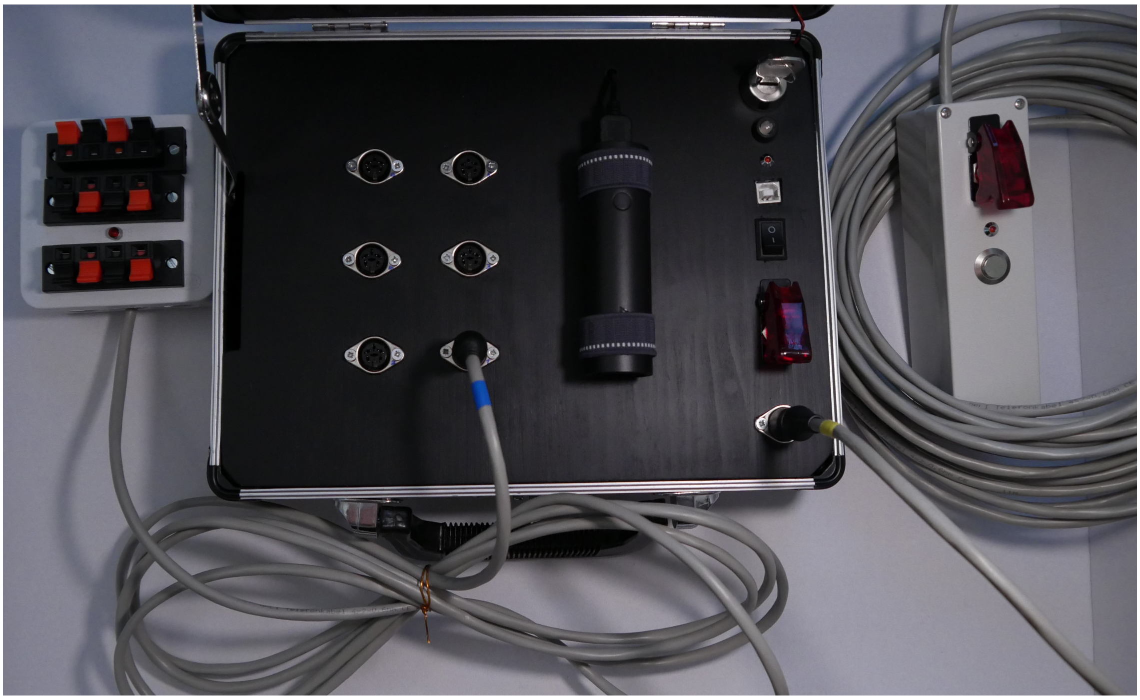


Figure 1: The resulting complete system with igniter and some modules.

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 regulated. This is not legal advice, so do your own research!

1.2 Concept

The device is divided into three units: controller, trigger and modules (See Figure 2). The controller is the center piece, that houses the micro controller which is a ATTINY 861[1] from Atmel. On board the controller are the main on/off key-switch, the arm switch,a USB port for programming, status LEDs and sockets for the trigger and modules. The trigger is connected by a 15m cable to the controller and has mounted a arm switch and the trigger button. There are six modules and each module is able to ignite eight bridge wire detonators (A-Type Only). The modules are also connected by cable to the controller. Two different cable lengths were used for the modules: 3x 4m and 3x 8m. Therefore the complete system is capable of setting of 48 detonators.

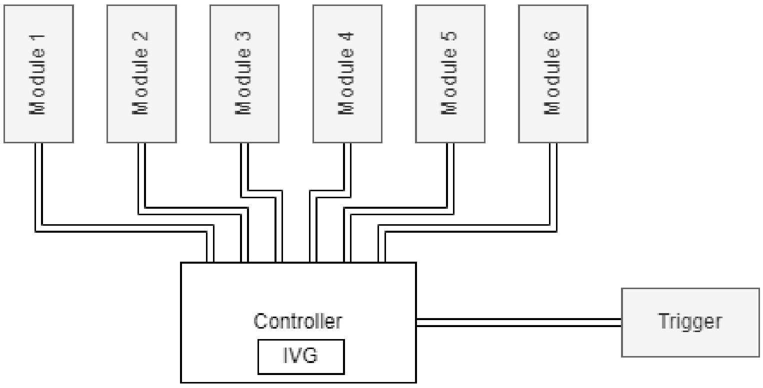


Figure 2: Basic layout of the three components controller, trigger and modules.

The system operates by the fire-and-forget principle, by which the user arms both the controller and the trigger and after pressing the trigger button the controller will automatically ignite the firework in the programmed sequence. No user input is needed after setting off. When the trigger is pressed the system goes into a 10s delay phase in order for the user to get to safety. After the delay phase is finished, the ignition phase is entered, where the programmed sequence will play through until the predetermined endpoint is reached. The trigger can be replaced with a RF-trigger although this is not recommend due safety and legal concerns in some countries. The delay period also serves as a fail safe, because if the system is triggered by accident, 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 go through the delay phase again.

The ignition sequence is programmed by USB via serial communication(See section 3.0.1). Programming the sequence can be accomplished by directly connecting to the serial port and typing the commands by hand or by using the Software provided(See section 4).

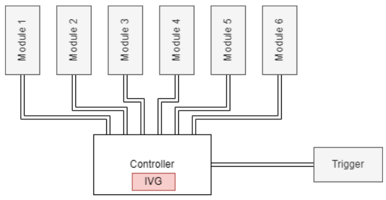
As the device is most likely placed in open-air field there is no way for it to be power by mains power, therefore it has to be powered by batteries. However, the usage of rechargeable batteries or LiPo-batteries was not desirable for this project, due cost issues and the additional requirement of protection circuits. A better alternative was found by using common 5V 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 chance some 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.

[1] https://www.mouser.com/datasheet/2/268/Atmel_2588_8_bit_AVR_Microcontrollers_tinyAVR_ATti-1315472.pdf

2 Hardware

As already explained in section 1.2, the device is split into three parts. This section will explore each part separately by looking into the design choices that were made. Although the controller is described as one unit, in reality consist of to distinct circuits. One is the ignition voltage generator (See section 2.1) which is responsible for generating the voltage/charge that is necessary for setting off the bridge wire detonators. The other circuit is the control logic that does the controlling (See section 2.2).

2.1 The Ignition Voltage Generator



The step-up convert shown in Figure 3 works by the basic principle of a step-up/boost converter by storing energy in form of a magnetic field inside a inductor and releasing the energy as a current into a capacitor. Repeat this process at high frequency and a higher voltage is created at the output compared to the input voltage. For a better explanation see the document about this topic by *Texas-Instruments*[2].

2.1.1 Circuit

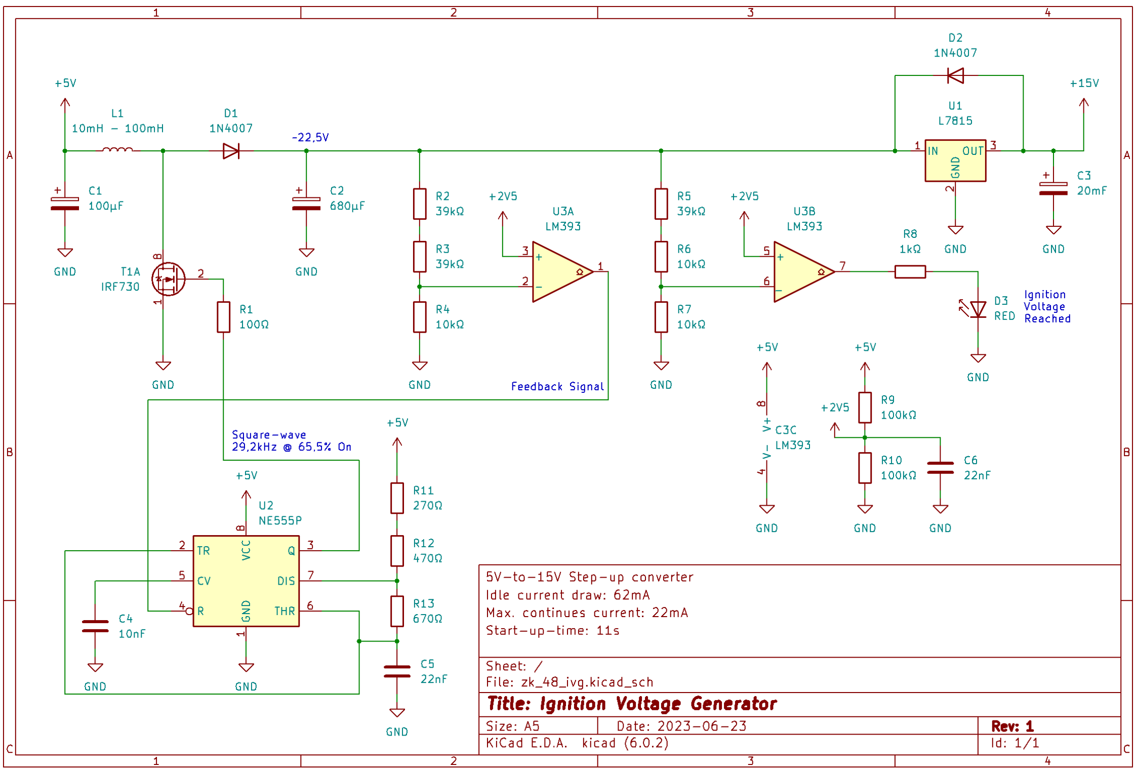


Figure 3: Circuit of the step-up converter that generates 15V DC for the ignition voltage

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

2.1.2 How does the circuit work?

The circuit shown in Figure 3 contains the popular NE555[3], the dual comparator LM393[4] and a 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 $C2$ an creating a voltage. We shall name this voltage 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 with turns off the NE555 if the intermediate voltage has reached $22,5V$. Using schmitt-trigger would result in a oscillating turning off and on of the feedback signal which is undesirable in this configuration. If the intermediate voltage reaches $22,5V$, the feedback signal will no longer be $5V$ or $0V$, rather it will drop to a constant $2,5V$. This is expected, but will result in a unpredictable behaviour at the NE555, which 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 does not matter, because the voltage already dropped significantly.

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 energy stored in the complete system with all six modules connected (Thus the total capacitance being $26mF$, but read more in **??**) which equates to around $3J$ and therefore not presenting any harm or danger to life[7]. Touching fully charged capacitors with wet hands 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 was used to turn on a red 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 a ignition voltage is present.

Note: Please note that the ignition voltage generator was designed by the author and is by no means ideal nor optimized. This was the first attempt at creating a step-up convert from scratch with components that were on hand. It does the job well (See section 2.1.3), but any bought step-up convert will do just fine and most likely better.

[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 Figure 3, a resistor with $4,7\Omega$ was placed into port 1 on module 1. This resistance is equal to two bridge wire detonators in series. This makes sure the system is tested in an less than ideal situation, because typically only one would be used. Figure 4 shows the complete test setup, with the pulse generator symbolically representing the controller. The system was programmed to fire port 1 on module 1 eight times with a $10ms$ delay between each pulse.

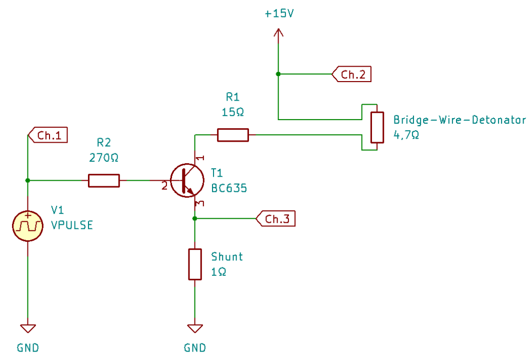


Figure 4: Circuit for testing stability of ignition voltage and current though a simulated bridge wire detonator.

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].

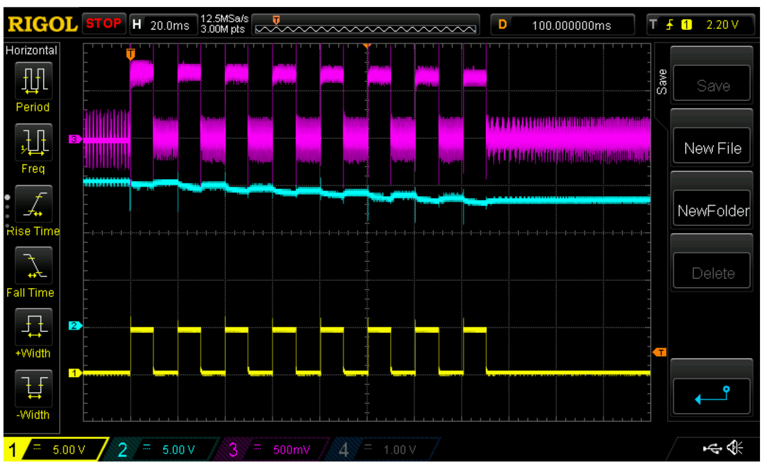


Figure 5: Oscilloscope recorded waveforms of eight pulses in close up.

The main objective of this test is to confirm that rapid firing does not affect the system ability to ignite further detonators. This can evidently be confirmed by looking at the curve of Ch.3 and Ch.2 in Figure 5. The ignition voltage is represented by Ch.2 which drops by only $2V$, thus being neglect able. By looking at Ch.3, which shows the current through the bridge wire detonator, its clearly recognizable that 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

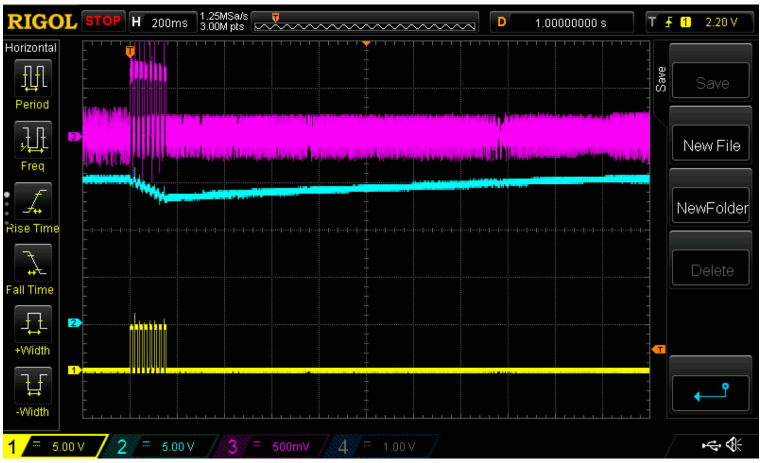


Figure 6: Oscilloscope recorded waveforms of eight pulses until returning to $15V$.

In Figure 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 better.

The third test focused in 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.

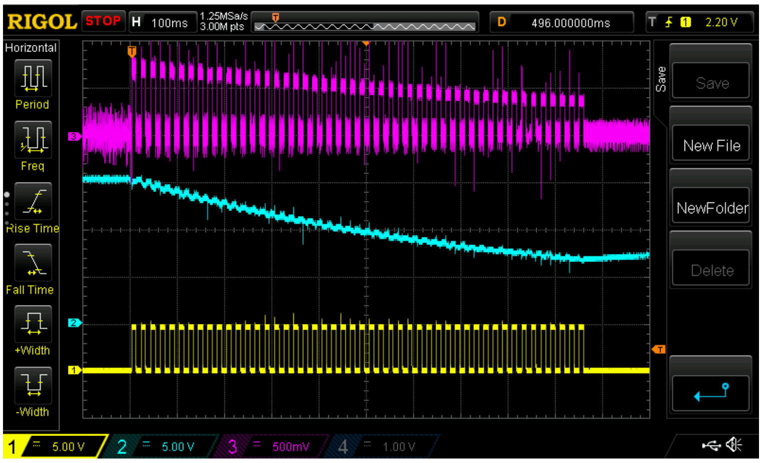


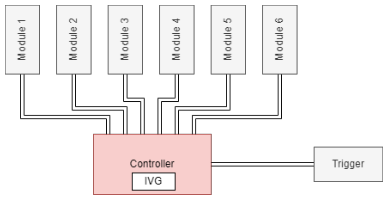
Figure 7: Oscilloscope recorded waveforms of 48 fire pulses.

The number of maximal fire pules was determined by counting the number of pulses until the current through the detonator fell below $500mA$. This current value was chosen arbitrary, as 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 fire pulses is about 24.

2.1.3.2 Conclusion

The ignition voltage generator is able to provide a steady voltage even under load(See Figure 4) and is able to ignite 24 bridge wire detonators with $10ms$ delay. This is just theoretical and needs to be confirmed with real detonators, however this is already promising to conclude proper operation. Although the generator performs well it has many flaws and should be subject of rigorous optimization. For example the ignition voltage should ideally not drop at all and remain steady 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. The projects goal is not to 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 and the trigger signal which are processed by the µC to correctly control all modules and controlling the status LED. The ignition voltage generator is also soldered on the physical circuit board together with the controller, but more about that in Section 2.2.4.

2.2.1 Circuit

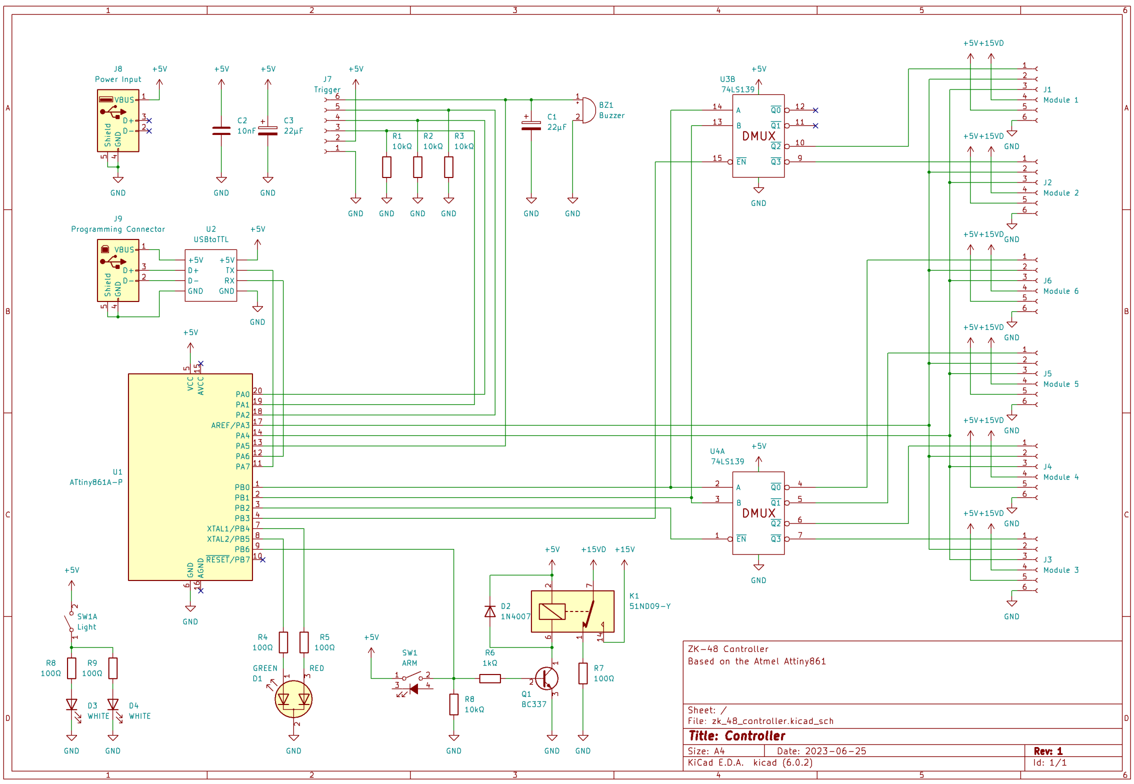


Figure 8: Circuit of the controller without ignition voltage generator.

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 Figure 8. Its purpose is the selection of the correct module to fire. To understand how this works its important to first explain how the µC fires a port on a module.

In Figure 8 notice that all module sockets DATA and CLK lines are connected together(For the pin-out see Section 2.2.3). The µC first serially transmits to all modules shift registers(See **??**) what port is about to be fired. In the second step the µC will select one out of the six modules which then fires the port that was set in the first step.

The selection process 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. Circuit design only allows to select one module at a time. Thus the system being unable to fire to ports on different modules at the same time. Currently 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. Our human eyes cannot pick up on such short delays and pyrotechnic is also not timed perfectly, therefore this does not impose a big problem.

The socket of the external trigger also falls into peripheral circuitry, but it does not contain any real 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, therefore needing to be pulled down. The local signal buzzer $BZ1$ is wired to the sockets BUZZER signal and its voltage is stabilized with the capacitor $C1$.

2.2.2.2 USB serial communication

For programming the µC has to communicate with a computer. This is the only bought circuit of this project because the Attiny861 does not have a build-in UART communication and no FTDI or other UART-to-TTL chip was easily and cheaply obtainable. Therefore the decision was made to save time and money by buying a UART-to-TTL module of *Amazon*.

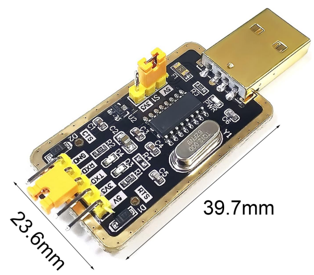


Figure 9: The bought UART-to-TTL converter from *Amazon*

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

[10] `https://www.ti.com/lit/ds/symlink/sn54ls139a-sp.pdf`

2.2.2.3 Arm safety circuit

This part of the controller circuit is shown in Figure 8 on the bottom. For safety reasons, the ignition voltage is 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 dangerous behaviour is explained by the shift registers inside of the modules. Most if not all shift registers when connected to power will take on random values inside their registers. If the output is disabled through the *Output Enable* pin on the 74HC595, this could not happen. However those enable pins are driven by the DMUX on the controller (See Figure 8) and those DMUX are controlled by the µC which takes more time to boot than the shift registers. Thus for a very short period ($< 20s$) turning on the some of the shift registers outputs and making it possible for a false ignition. Although this cannot be prevented, it is possible to take away the ignition voltage and pulling down the modules ignition voltage line with a 100Ω resistor (See resistor $R7$ in Figure 8). Relay $K1$ is only connecting the ignition voltage to the modules power lines if the system is armed and therefore making it impossible to accidentally set of pyrotechnics prematurely.

2.2.2.4 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 complete controller to illuminate the interface. The circuit can be found in the bottom left corner in Figure 8, although the LEDs are not soldered onto the circuit-board. They are place inside of the lid, thus shining downwards onto the interface if the case is opened.

2.2.3 Socket and Plugs

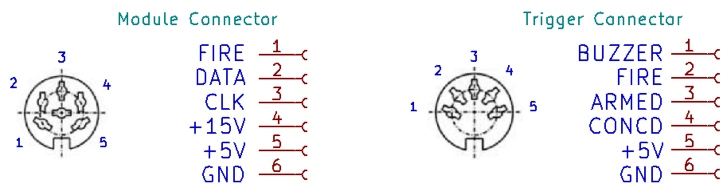


Figure 10: The pin-out of the trigger and modules socket/plug.

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

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

Figure 11: DIN socket and plug of the modules.

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

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

2.2.4 Circuit board

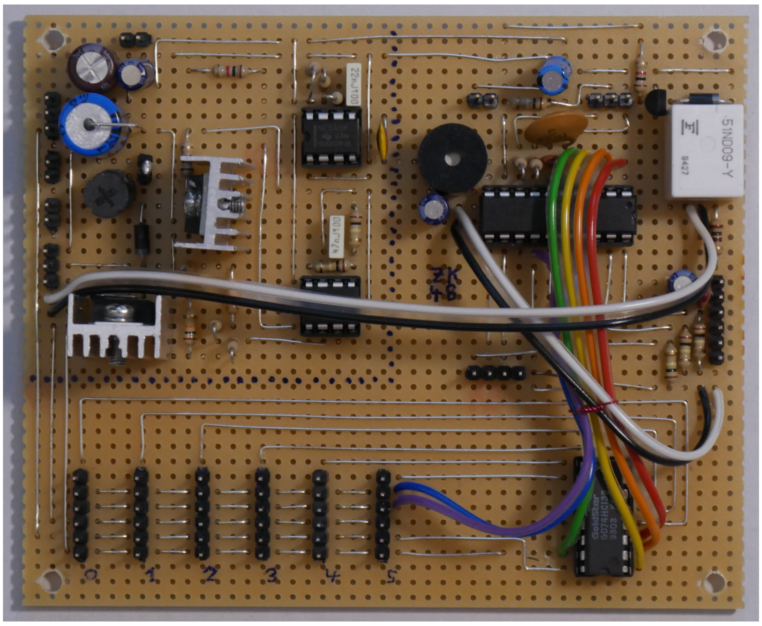


Figure 12: The controller circuit (See Figure 8) and the ignition voltage generator (See Figure 3) soldered onto a perfboard.

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

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

2.2.5 Housing of the Controller

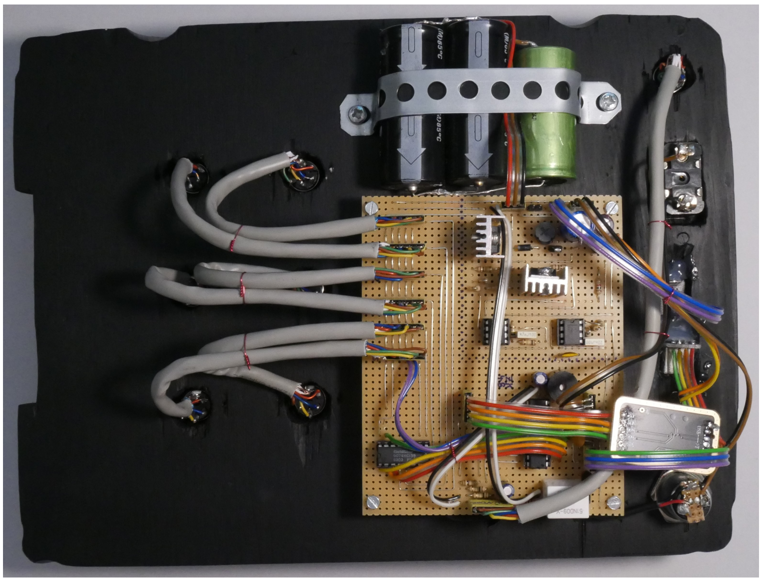


Figure 13: The circuit board depicted in Figure 12 mounted and wired onto the backside of the devices interface.

The image in Figure 13 shows the controller with all peripheral devices connected. On the top are the two big capacitors that store the ignition and intermediate voltage, secured to the board by a metal band.

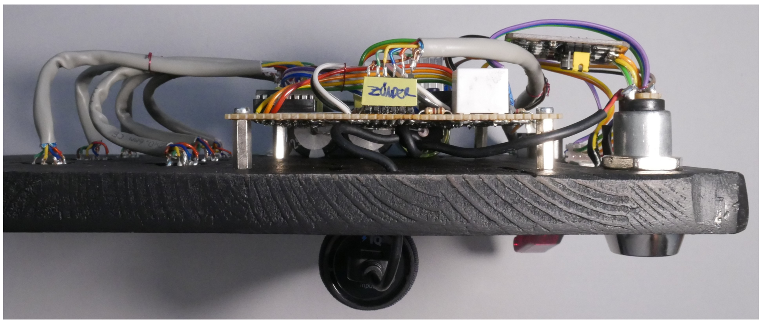


Figure 14: The circuit board depicted in Figure 12 mounted and wired onto the backside of the devices interface viewed from the side.

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 painted black and everything was screwed on. In Figure 14 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[12] with shielding. This cable was also the choice for externally connecting the trigger and modules to the interface.

[12] `https://amzn.eu/d/65ZALnq`

Figure 15: The gun case used for housing the controller.

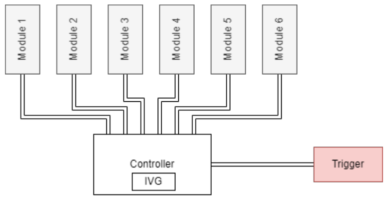
Source of Figure 15: `https://amzn.eu/d/eWSlyFs`

A gun case was bought of *Amazon* (See Figure 15), and the cushioning in the lower part of the case was removed to make room for the controller. The complete contorller interface was put into a case and screwed from the sides. Figure 16 depicts the finished controller turned 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 hiden behind the cushioning. In Figure 16 the wires can be seed coming from the top part of the case going to the lower part(See Figure 16 right top corner).

Figure 16: 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 setting off the pyrotechnic show. Its purpose is to tell the controller when to start but also tell the user that the state the controller is currently in. This is very important because the user must be far way from the controller when the pyrotechnics are ignited, but also needs to be informed if the system is working properly.

2.3.1 Circuit

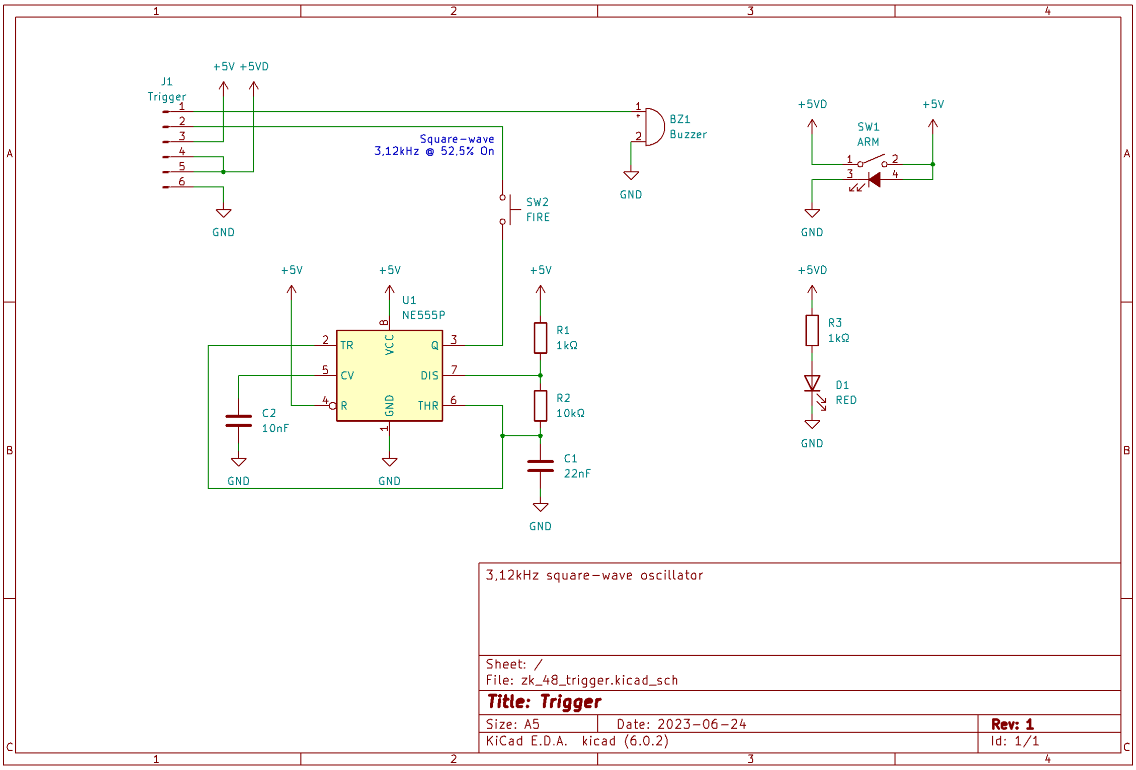


Figure 17: The circuit of the external trigger.

2.3.2 How does the trigger work?

The trigger receives one signal and sends three signals back. The first input signal is going to buzzer and is connected to the buzzer on board the controller (See Figure 8). This buzzer gives the user feedback on the state of the system by changing the frequency of the sound produced by the buzzer. But more about this topic 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 straight 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 powers up 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 placed onto the FIRE line of the trigger, therefore starting the firing sequence. To indicate if the trigger has power, a small LED $D1$ is also present on the trigger.

2.3.3 Housing of the Trigger

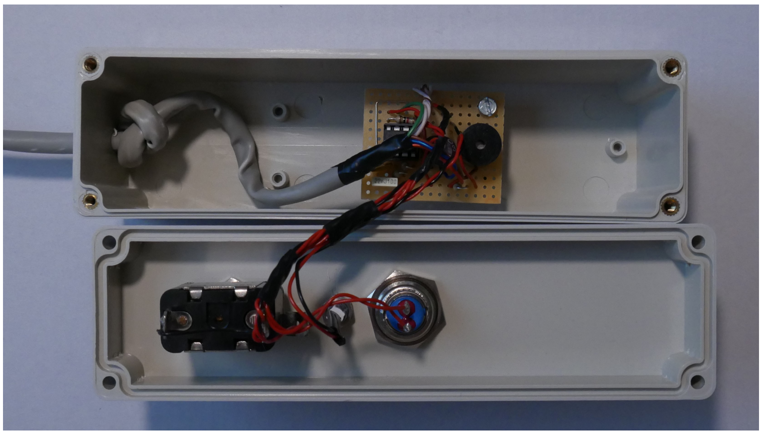


Figure 18: The external trigger circuit mounted inside its case.

The circuit of the trigger shown in Figure 8 was soldered onto a perfboard. Together with the circuit, the arm switch, power LED and fire button were mounted into a ABS housing with the dimensions of 150x45x55mm as shown in Figure 18. The trigger uses a telephone cable, as described in Section 2.2.5, with a length of about $15m$ to connect to the controller. In ?? the complete controller is visible.

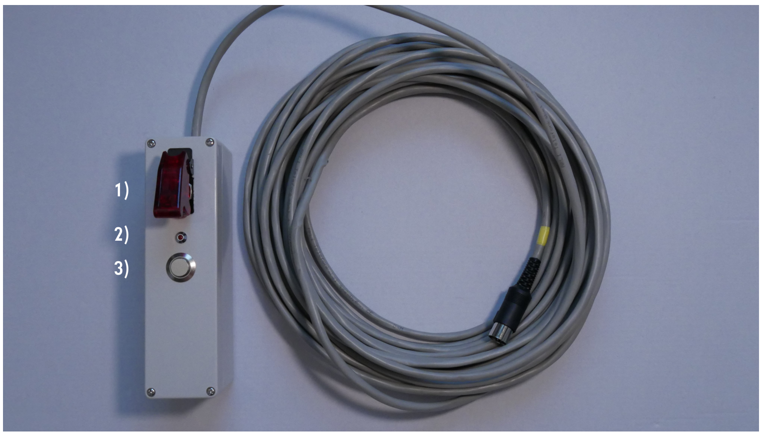
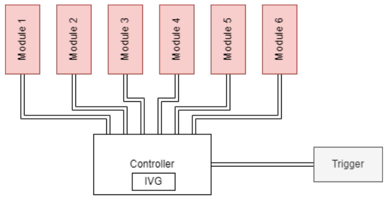


Figure 19: The external trigger with its cable.

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

2.4 Ignition Modules



The ignition modules are responsible for the ignition of the pyrotechnic effects, therefore carry a large responsibility. There is no margin of error, as the whole system depends on the ignition modules proper function.

2.4.1 Circuit

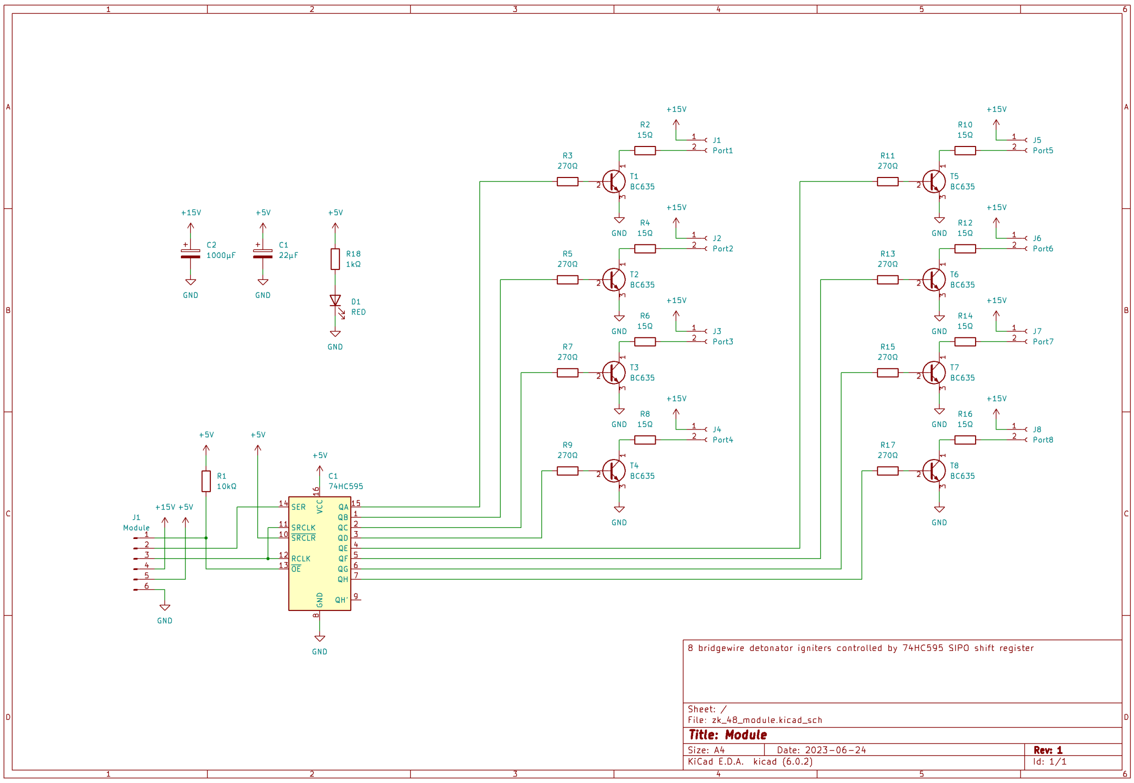


Figure 20: The circuit of the ignition module.

2.4.2 How does the Ignition Module work?

2.4.2.1 Ignition Circuit

When setting off a bridge wire detonator, a current bigger than $500mA$ must flow for guaranteed ignition. This poses some challenges, because the switching transistor must be able to handle such currents repeatedly . Furthermore, considering that detonators can be faulty, for example have an internal short-circuit, those currents should not destroy the transistor. As well as the actual electrical requirements to the circuit, the cost of each module should stay on the lower end, as six modules are going to be build with eight ignition circuits.

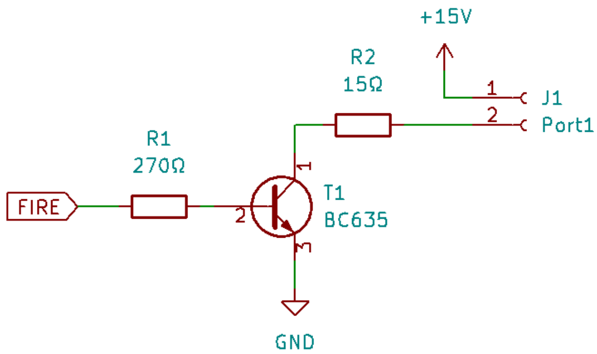


Figure 21: The circuit responsible for setting off one bridge wire detonator inside the ignition module.

All aforementioned considerations were dealt with by limiting the current through the transistor. Limiting the current was accomplished by using a 15Ω resistor after the bridge wire detonator (See Figure 21 $R2$) which limits the current at $15V$ ignition voltage to maximal $1A$. Knowing the maximal current and considering the other requirements, the NPN transistor BC635[13] in a TO-92 package, was the best fit. Its continuous collector current is equal to $1A$ and a costs 9 cents per piece makes this choice ideal. To drive the BC635 a 270Ω resistor was used to limit the base current to about $16mA$ (See Equation (2)), that results in the saturation of the transistor. Figure 21 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 ignition voltage. The reason why the ignition voltage is $15V$ and not $5V$, which would make things much simpler, lays inside Ohm's law: If the ignition voltage is $5V$ instead of $15V$ and the current is still limited to $1A$ in by a 5Ω resistor, a reduction of the current through the detonator will occur. The calculations below (Equation (3) and Equation (4)) calculate the current for both cases, by simulating a bridge wire detonate with the same resistor value of $4,7\Omega$ as used in Section 2.1.3.

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

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

Compared result Equation (3) to result of Equation (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 are connected in series(Parallel connection is not recommend in general). Of course a stronger transistor could be used but this could raise cost.

[13] 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[14].

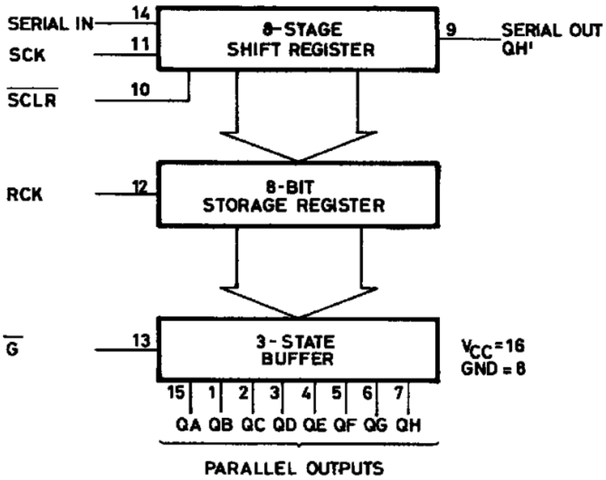


Figure 22: Functional diagram of the 74HC595

Source of Figure 22: ***https://cdn-reichelt.de/documents/datenblatt/A240/74HC595%23STM.pdf***

The 74HC595 is made up of three parts: the shift register, a register and a tri-state buffer(See Figure 22). To fire a port, the µC sends a byte mask serially to the shift-register (In Figure 22 see pin 14 SERIALIN and 11 SCK) where one bit is set, indicating which port is being fired. Because the register clock RCK and shift register clock SCK are wired together (See Figure 20) the register will take on the values from the shift register. As explained in Section 2.2.2 "Peripheral Managing and Controlling Logic" the µC afterwards selects the correct module being fired which will result in pulling low the enable pin on the tri-state buffer (pin 13 in Figure 22). Thus outputting the stored bit mask of the register onto the parallel outputs. Figure 20 shows that each output is directly connected to one ignition circuit, whereby the setting of an output fires a detonator.

2.4.2.3 Additional circuits

To reduce the currents through the cable to the ignition modules, a large $1000F$ capacitor C_2 was added to the $15V$ ignition voltage (See Figure 20). As charge would be stored closer to detonator theoretically this should reduce currents, however this is speculative and the capacitor might not be needed at all.

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

2.4.3 Housing of the Ignition Modules

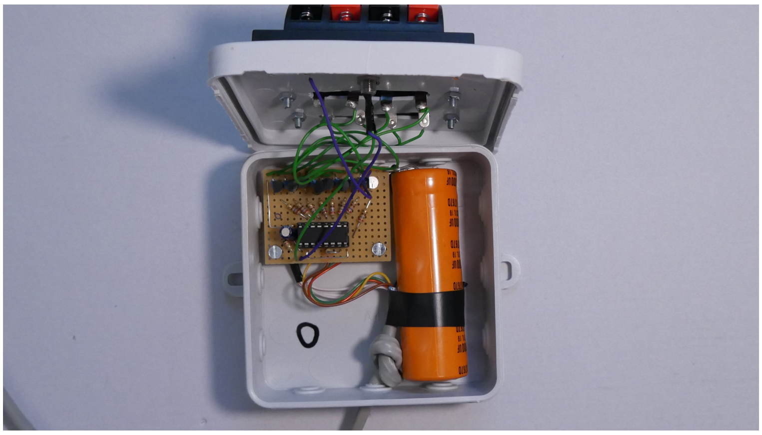


Figure 23: The ignition module from the inside.

The circuit got soldered onto a perfboard and for the housing a common electrical junction box was used as it is cheap, light weight, easy cut-able and can be screwed against something. For connecting to the controller, four pieces of $4m$ and four pieces of $8m$ telephone cables were cut and soldered to the each of the eight modules circuit boards as seen in Figure 23. Also visible in Figure 23 is the orange stabilizing $1000F$ capacitor $C2$ seen in Figure 20.

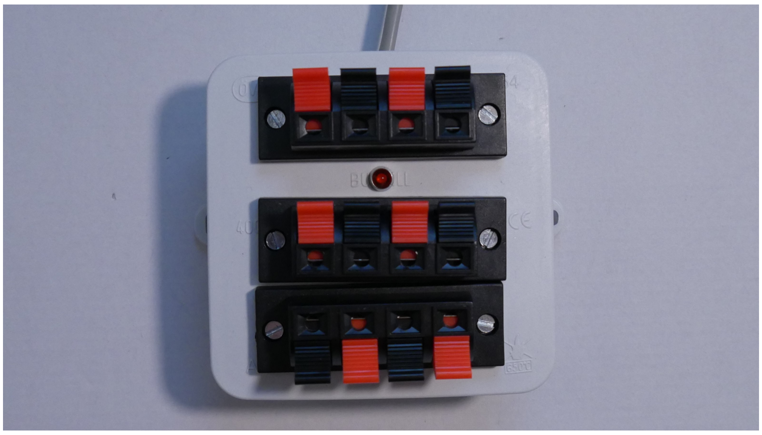


Figure 24: The complete ignition module with eight ports on the bottom and one power rail on the top.

To connect the bridge wire detonators to the circuit speaker terminals were used. In Figure 24 the bottom two terminals are 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 the housing this was necessary.

2.5 The Complete System

3 Firmware

3.0.1 USB Connection

4 Software

5 Recognitions

All circuits were drawn with the help of *KiCad* 6.0[15]

All flowcharts and diagrams were drawn with the help of *Drawio*[16]

[15]`https://www.kicad.org/`
[16]`https://app.diagrams.net/`