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DIGITAL REVERSE LOOP MODULE FOR MINIATURE RAILWAY LAYOUTS

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Abstract: The design and construction of a realistic model railway layout is challenging because of the many aspects that must be considered, such as matching everything together, observing an existing railway route or imagining one, designing the analog or digital custom electronic command and control system, respecting the operating and standardization rules of the available components and devices etc. Most of the miniature railway layouts use the DC (Direct Current) and DCC (Digital Command and Control) systems, with two metal rails on plastic sleepers that feed the trains with electricity and control. The double-track railway systems are quite easy to design and operate, because the trains that reach the end of the route can return to their departure by simply passing on the parallel line of the same route. However, on the single-track railway layouts, the trains must reverse on the same line by means of reverse loops fitted with turnouts, which raises big problems of DC voltage or DCC signal polarity. The rails of the single-track reverse loop must be fully insulated from the rails of the main line; otherwise, they would immediately short-circuit them because of the reversing operation itself. Thus, the loop rails must be powered in such a way as to prevent polarity mismatches both at train entry and exit. The authors have designed, made, and tested a digital microcontroller-driven module that automatically matches the DCC signal polarity of the single-track reverse loop to that of the main line, with or without driving the loop turnout accordingly.
Key words: DCC, model trains, railway layout, reverse loop, microcontroller, short-circuit detection.

1. INTRODUCTION

The model trains are nowadays designed, engineered, manufactured, assembled, and driven by means of state-of-the-art technologies and materials. Besides collecting, displaying, entertainment etc., they can be used for study, modelling, simulation, validation, development etc. For example, the Darmstadt Railway Operations Field (EBD) is a joint project of the three partners: Academic Working Group on Rail Transport (AKA Bahn), DB Training, Learning & Consulting Institute for Railway Systems, and Railway Technology of the Technical University of Darmstadt. Since 1914, a giant model railway layout has been built and developed, which simulates railway operations on approximately 500 square meters and the equivalent of about 135 km of track with over 17 stations, crossovers, and junctions, using a wide variety of interlocking systems – from mechanical to modern electronic systems. Depending on the application, the operating points can be controlled with different interlocking systems. Everything is possible, from the central operations control room, where two train dispatchers manage all operations on the layout, to the manned operation of all signal boxes at individual stations, with over 18 train dispatchers and switchmen on duty. The railway operations field is used by project partners for a variety of activities, including training, testing of novel processes, and research [1].

Model trains are also used for teaching mechanical and electrical phenomena. For example, the motion of an electric toy train engine that is powered by a time-dependent voltage and travels on a horizontal track can investigate effects such as friction, the electrically induced torque and electromotive force of the motor, resistance, inductance, and applied voltage to identify the impact of each on the train’s performance [2].

Various digital modelling activities, including formal ones, are undertaken by the railway industry for design, development, validation, qualification, and exploitation. This introduces trends toward regrouping models to obtain more significant results together with a larger scope, prefiguring digital twins [3]. Other approaches imply the use of more advanced simulation techniques, with or without physical model trains, such as train derailment accident simulation with real-virtual mapping and real-virtual interaction [4].

There are two main approaches for driving the miniature model trains, DC and DCC, both with their advantages

and disadvantages. There are regulations for both systems, expressed by NMRA [5], and the digital systems and accessories are available from renowned manufacturers and by custom-made production [6].
Extended miniature railway layouts feature long routes for the trains, and many of them imply the travelling of trains from point A to point B and back. So, in most cases, it becomes necessary to think about returning trains on the same route, which requires the design and use of reverse loops at both point A and point B. The reverse loops are simple if the model railway layout features double-track lines, but they require the use of turnouts if single-track lines are used, and these pieces of railway equipment can raise lots of mechanical and electrical problems, which are addressed and solved by the digital reverse loop module designed, made, and tested by the authors.

2. MATERIALS AND METHODS

2.1. Turnouts

DC/DCC miniature railway layouts are based on two metal rails on plastic insulating sleepers, which always have opposite electric potentials, static (DC) or alternating (DCC), which means that under no circumstances should they come into electrical contact. This is why the miniature turnouts, crossings and such other trackwork devices are masterpieces of fine mechanics and complex internal electric circuits, because the rails must cross without causing short-circuits and without interrupting the collection of electric current by the passing train.
Fig. 1 shows a 1:87 model turnout with an insulated plastic frog fitted with conductive metal strips that reduce the no-power gap while the train passes over it. Fig. 2 shows the components and notions of a real-life turnout [7]. The working principle is the same for both real and miniature turnouts: during the facing move, the wheel flanges of the incoming train are directed by the switch rails (or blades) towards the through exit or the diverging exit. During the trailing move, the switch rails should match the direction of the incoming train; otherwise they risk derailment if they are locked in place.
The ensemble formed by the crossing nose and the wing rails is called “frog”, and here the rails cross. The miniature turnouts can be built with insulated frogs (Fig. 1), polarized metal frogs, mobile metal frogs etc., but under no circumstances should they produce any electrical contact between the two crossing rails.

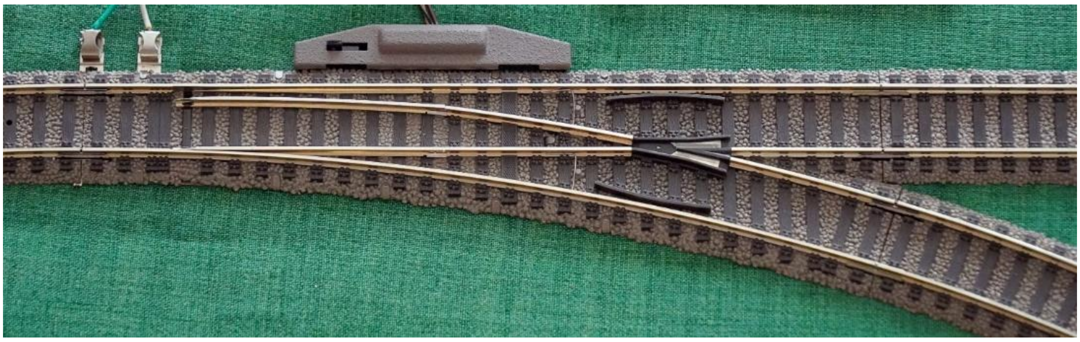

Fig. 1. 1:87 model turnout with insulated frog.

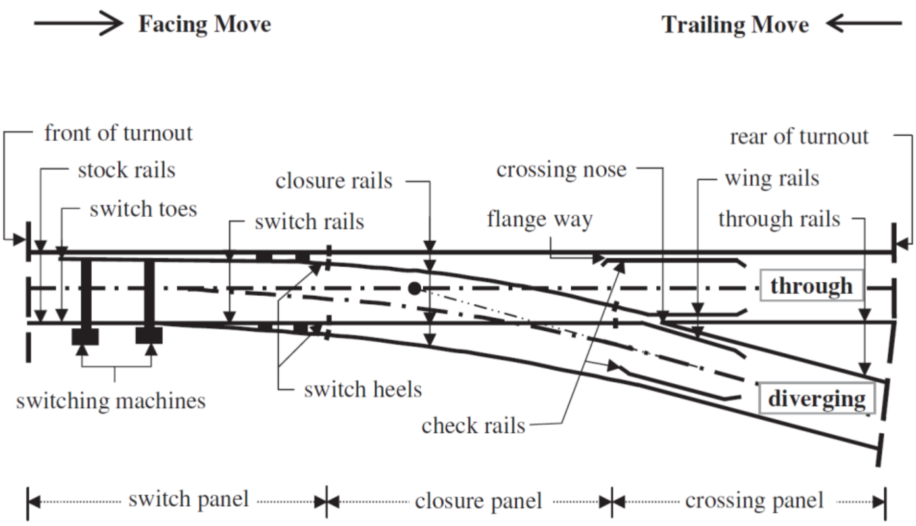

Fig. 2. Real-life turnout, with components and notions. [7]

2.2. Reverse Loops

Within a double-track layout (Fig. 3), one track can be used for travelling from point A to point B, and the parallel track for returning to point A, so turnouts are not required for the reversing of trains. The reverse loops are more or less "U"-shaped with two ends. The reverse loop at point B has the entry from track A-to-B and the exit to parallel track line B-to-A, and the one at point A has the entry from track B-to-A and the exit to parallel track line A-to-B. Thus, the two rails will never cross and/or come into electrical contact.

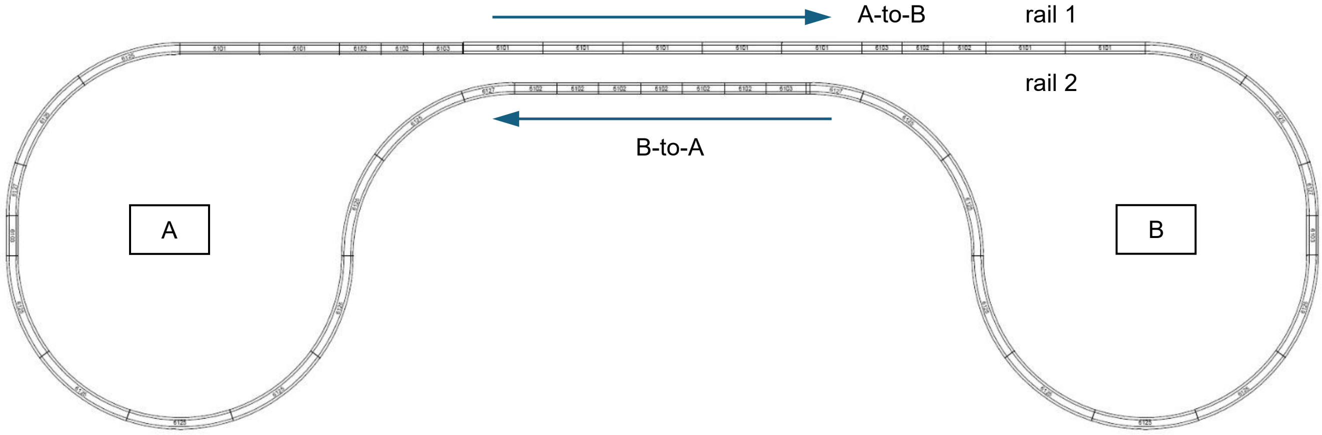

Fig. 3. Double-track miniature railway layout (simplified).

The situation changes dramatically when a single track is used, because the trains must reverse on the same track. There are two solutions: to use push-pull train sets and buffer stops at both ends of the single track, or to use normal trains and reverse loops at both ends of the single track (Fig. 4). The last case is more spectacular than the first one, but the danger of short-circuit increases greatly because the shape of the reverse loops and the turnouts will bring together rail 1 and rail 2, and we must avoid their electric contact by using insulating fishplates at the rear ends of both turnouts. Of course, this operation will leave the loops unpowered, so we must think of an automated device that will power the reverse loop in accordance with the position and travelling sense of the train itself, so that the polarity of the loop will match the polarity of the main track when the train arrives at the loop and when the train leaves the loop.

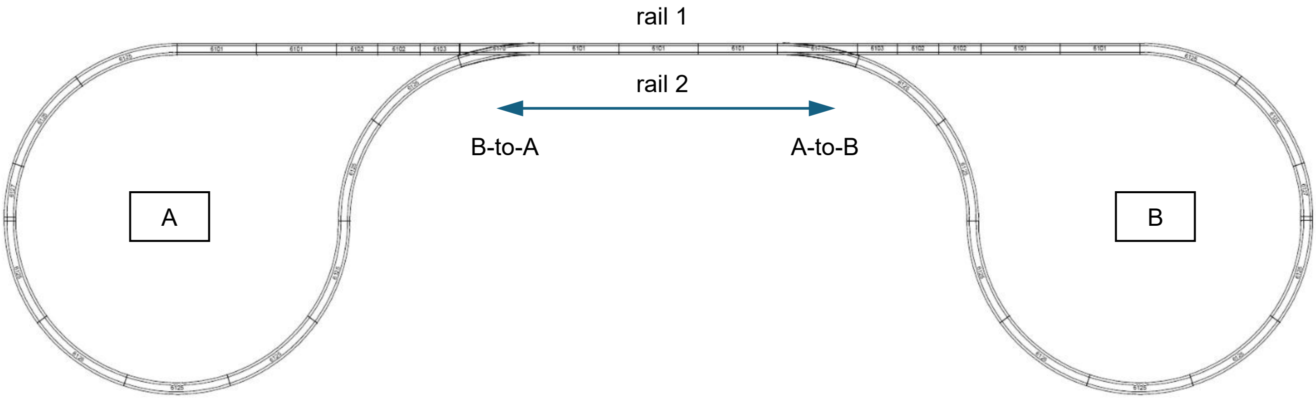

Fig. 4. Single-track miniature railway layout with reverse loops (simplified).

According to the DCC working principle, the DCC signal polarity that is received by the locomotive decoder is not important, which makes it possible to switch the polarity of the reverse loop while the digital train is running along it. The polarity switching of the loop must be performed fast enough so that the locomotive decoders do not notice and continue their operation.

2.3. The Digital Reverse Loop Module

The polarities of the DCC signal within the single-track reverse loop are shown in Fig. 5, where the sense of travel is shown by the curved black arrow. When the train enters the loop by the turnout diverging end (Fig. 5.a) and when the train exits the loop by the turnout through end (Fig. 5.b), the polarity of the loop must match the polarity of the main line. As mentioned before, the rails of the reverse loop are separated from the rails of the main line by means of insulating plastic fishplates, and the reverse loop itself will be powered by an automatic module that switches the polarity according to the position and traveling sense of the passing train.

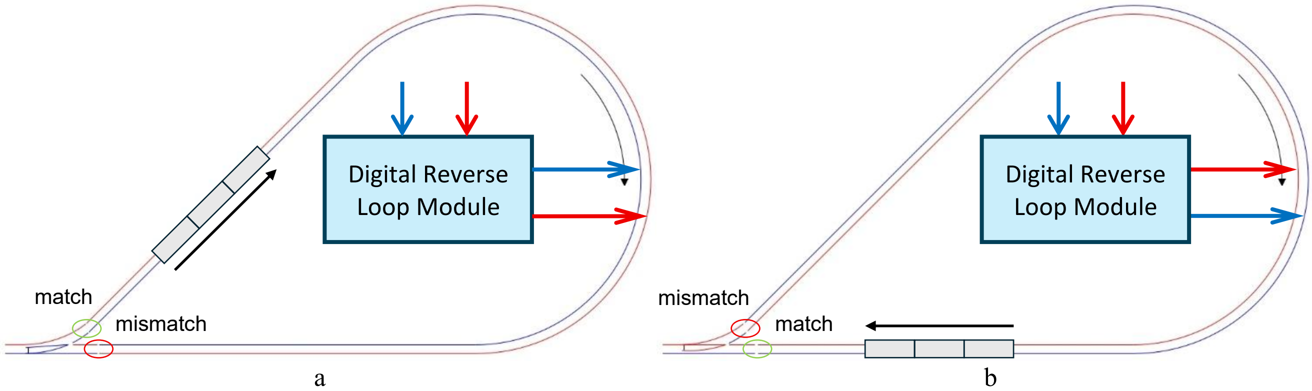

Fig. 5. The polarities of the DCC signal: *a* – the train enters the loop by the turnout diverging end, *b* – the train exits the loop by the turnout at the end.

Obviously, a short-circuit will occur if the polarities of the loop and of the main line do not match, and a metal wheel makes an electrical contact between the opposite potentials of the adjacent rails. This momentary a short-circuit will trigger the module to quickly reverse the polarity of the loop, thus cancelling the short-circuit immediately and allowing the train to continue travelling across the reverse loop without interruption. Furthermore, due to the fast polarity switching, the short-circuit protection of the central command station will not be triggered, and the operation of the entire railway system will not be affected.

Therefore, the module must provide almost instantaneous DCC signal switching, which means electromagnetic relays cannot be used for this purpose. So, the authors decided to use MOSFET power transistors instead. Fig. 6 shows the branch that makes the direct connection of the loop rails to the main line rails. The other branch that makes the reversed connection is identical, but the connections to the loop rails are reversed. The connectors X2-1and X2-2 lead to the rails of the main line, and the connectors X1-1 and X1-2 lead to the rails of the reverse loop. The resistor R22 (15 kΩ) is connected in parallel to the rails of the reverse loop.

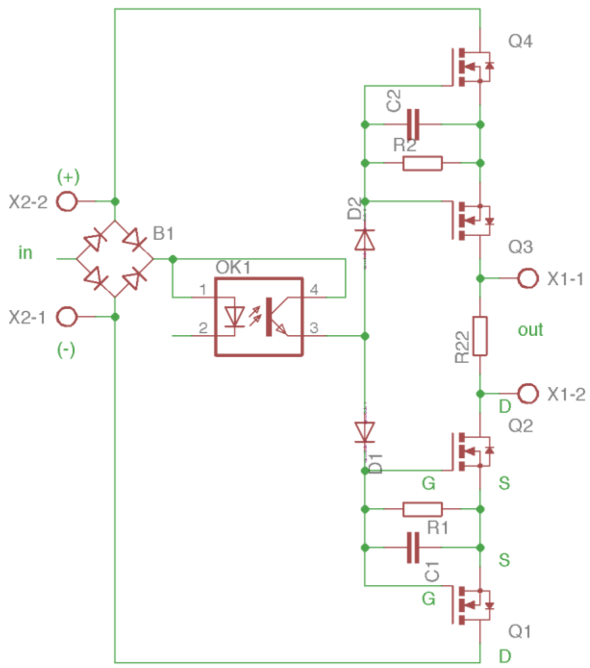

Fig. 6. The direct connection branch of the automated module.

When the LED of the optocoupler OK1 is off, its internal transistor and all four MOSFETs are blocked, and no DCC signal can access the rails of the reverse loop.

When the LED of the optocoupler OK1 is on, its internal transistor opens, and the rectified DCC positive voltage arrives at the anodes of diodes D1 and D2. To begin with, let’s assume that the DCC signal has polarity + (plus) at X2-2 and – (minus) at X2-1. The rectified positive DCC voltage runs through the components

B1 – OK1 – D1 to the resistor R1 and the gates of MOSFETs Q1 and Q2, which have their sources S connected. Q1 is shunted by its forward-biased internal diode, which also gets the right terminal of resistor R1 drawn to the minus potential of X2-1. Thus, across R1 there will be a voltage drop of 12.3V, which is the DCC amplitude of 15 V minus the voltage drops across B1, OK1, D1, and the internal diode of Q1. This voltage drop charges the capacitor C1 and opens the channels of both Q1 and Q2, therefore, the output terminal X1-2 gets connected to the input terminal X2-1, and the negative DCC potential is transmitted from the main line to the loop.
In a similar way, the channels of transistors Q3 and Q4 open and connect the output terminal X1-1 to the input terminal X2-2. Still, there is a slight difference because the right terminal of resistor R2 will be drawn to the negative potential of X2-1 by means of the forward-biased internal diode of Q3 and resistor R22 in parallel with the internal resistance of the train that runs across the loop (if any). The voltage drop across R2 would be approximately 5V, which charges capacitor C2 and opens the channels of Q3 and Q4. However, this leads to the blocking of the diode D2 because its cathode becomes more positive than its anode, so the voltage drop across R2 decreases as C2 discharges. Thus, Q3 and Q4 will start to partially close until diode D2 starts to open, which will again increase the voltage across R2 and C2 etc. This leads to an equilibrium state with Q3 and Q4 partially open. The 10 nF capacitance of C2 ensures that the R2 voltage decrease is delayed long enough so that the module can correctly handle both the “0” bits (116 µs) and the “1” bits (58 µs). Therefore, the positive DCC potential is transmitted from the main line to the loop.
When the polarity of the main line DCC signal is reversed, we get the negative potential at X2-2 and the positive potential at X2-1, and the above-described phenomena repeat in a similar way but on the opposite halves of the branch. The capacitors C1 and C2 keep the channels of Q1 ÷ Q4 open even when the DCC polarity changes, because MOSFETs are bidirectional, and their across voltage gets refreshed at every polarity switch.
The branch that has been presented makes the “direct” connection between the rails of the main line and the rails of the reverse loop. The “reversed” connection is made by a second identical branch, as mentioned before.
The measurements showed that the switching duration of this module is 1 ms, which makes it much faster than relays (over 20 ms) and the commercially available module NCE AR-10 (16 ms) [8].
Fig. 7 shows the electronic diagram of the digital reverse loop module. The power section of the module is driven by the microcontroller command section. To trigger the polarity switching, the authors chose the detection of momentary short-circuits caused by a metal wheel, which makes an electrical contact between the opposite potentials of the adjacent rails when the polarity of the loop and the polarity of the main line mismatch. Several ways to detect these short-circuits are known, such as the decrease of the DCC signal amplitude [9], the imbalance of the currents in the rails [10], the increase of the current delivered to the rails by means of inductive transducers [8] etc. The authors chose the current sensors based on the integrated circuit ACS712 [11]. Two such modules were used, one for each power branch of the device. The output signals of these modules are continuously assessed by the two comparators of the PIC16F689 microcontroller. The polarity switching is triggered when the previously set threshold is exceeded. The current threshold can be set according to the requirements of the railway system, at 0.84 A, 1.13 A, 1.69 A, 2.25 A, 2.53 A or 3.38 A, of which we chose 2.25 A. This threshold value is sufficient for the loop itself and is below the short-circuit current threshold of the central command unit.

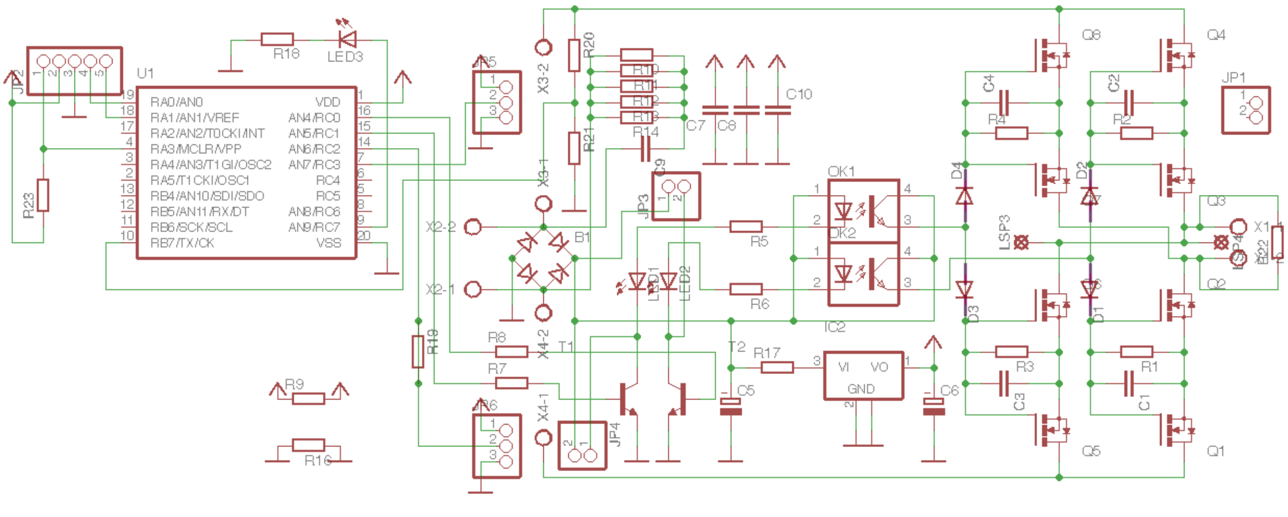

Fig. 7. Electronic diagram of the digital reverse loop module.

The rails of the main line are connected to terminals X2-1 and X2-2 and the rails of the reverse loop are connected to terminals X1-1 and X1-2. The “direct” connection is made by the power branch with transistors

Q1 ÷ Q4, and the “reversed” connection is made by the other power branch with transistors Q5 ÷ Q8. Both power branches are activated by their respective optocouplers, of which the LEDs are activated by the microcontroller by means of two NPN SMD transistors T1 and T2. Because the LEDs of the optocouplers cannot be seen, the authors inserted white SMD LEDs in series with the driving circuits of the optocouplers. Thus, transistor T1 will activate both LED1 and the LED of the optocoupler OK1, which will activate the “reverse” branch. In a similar way, the transistor T2 will activate both LED2 and the LED of the optocoupler OK2, which will activate the “direct” branch. The two current sensors are placed in series between the inputs from the main line rails and the parallel pair of the power branches. A sudden current increase detected by one sensor means that a metal wheel touched two adjacent rails at opposite potentials and produced a momentary short-circuit, thus the polarity of the reverse loop does not match with the polarity of the main line, so the microcontroller will deactivate the mismatched branch and will activate the other branch. Therefore, the module will switch the polarity of the reverse loop rails if such momentary short-circuits are sensed. The central digital command station will not react to these short-circuits because its own short-circuit threshold is superior to the one of the module.
The rectifier bridge B1 receives the DCC signal from the rails of the main line, powers the driving circuits for the two power branches and, by means of a voltage stabilizer 78L05F, powers the microcontroller with 5 V.
The authors designed the PCB of the module (Fig. 8) by means of Eagle software [12], with the intention of using mostly SMD components. The design was printed on transparent foil, and the raw PCB with positive photoresist was exposed to UV light through the printed foil. Then the well-known chemical procedures were performed: developing, etching, tinning. Fig. 9 shows the assembled digital reverse loop module.

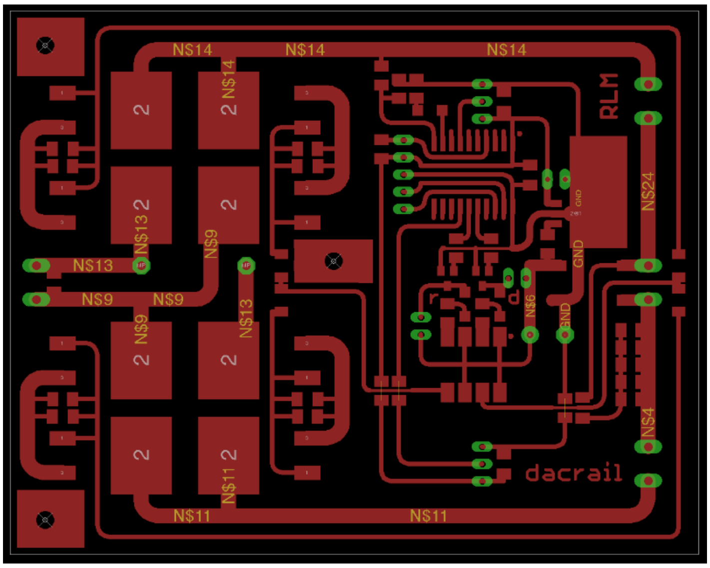

Fig. 8. PCB design for the digital reverse loop module.

Fig. 9. The digital reverse loop module.

3. RESULTS AND DISCUSSIONS

Fig. 10 shows the miniature railway layout used by the authors to test the digital reverse loop module, made of Fleischmann H0 Profi-Track items [13]. H0 (“Halb-Null”) refers to the 1:87 scale. The DCC signal is fed to the main line from the outputs of the Lenz Set 101 central digital command station. The digital reverse loop module is connected as described before, connectors X2-1 and X2-2 to the main line and connectors X1-1 and X1-2 to the reverse loop. During the tests, the authors observed that both wheels of an axle don't need to touch adjacent rails simultaneously. Thus, the insulating fishplates are offset by a section of track, so that only one metal wheel would trigger the reverse loop polarity switching, in case of polarity mismatch.

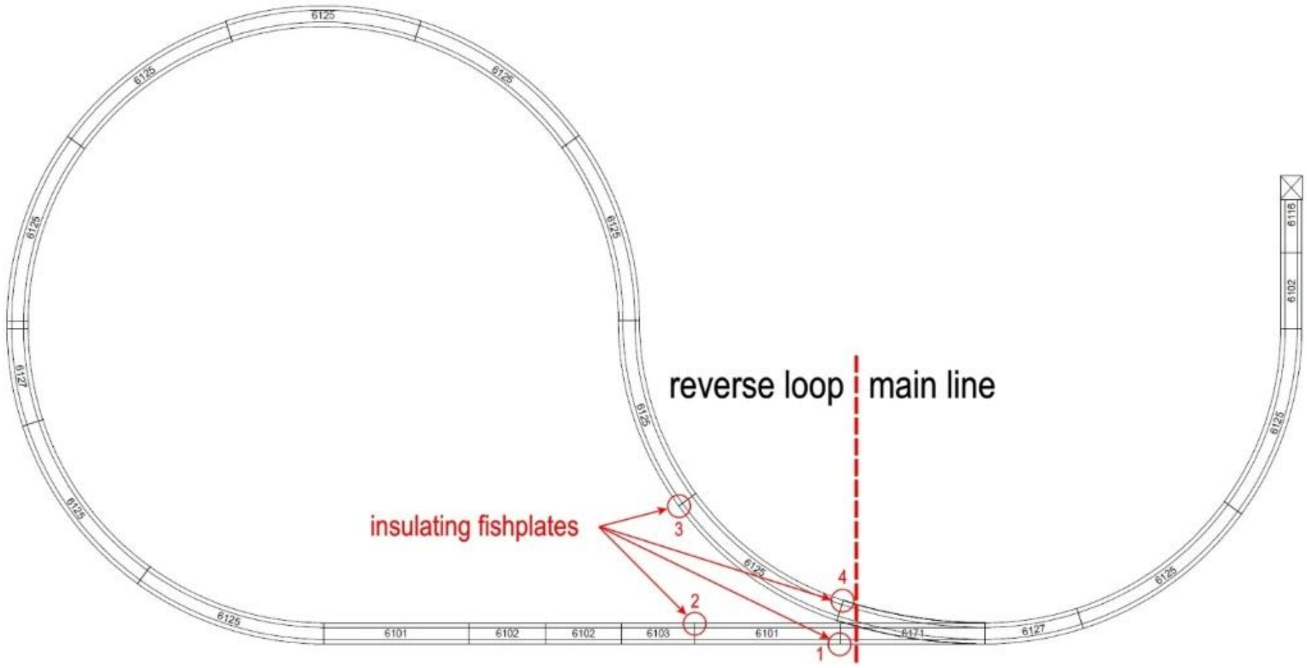

Fig. 10. Test track for the digital reverse loop module.

The model railway turnouts come in many shapes and modes of operation. Their blades may move freely, may be spring-loaded, may be operated by a turnout motor, may be locked in place etc. The model railway turnout in this test track (Fig. 1) has spring-loaded blades, which can be operated by an electromagnetic universal motor with end-of-switching. When a train enters the turnout by its rear end, and the blades are set on the other exit, the wheels can push away the blades so the train can safely pass towards the front end of the turnout, and then the blades return to their previous position on their own.

The authors used several digital locomotives from their personal collections for the tests, first without activating the turnout motor. Fig. 11 shows one such test, where the spring-loaded blades of the turnout are set for the through exit. The other test was run with the blades set for the diverging exit and performed similarly.

The steam locomotive comes from the main line boiler first, and the module is set on the “reverse” mode, shown by the light of the corresponding white SMD LED (Fig. 11a), which means that the polarity of the reverse loop matches the diverging exit. The locomotive is guided by the turnout to the through exit (Fig. 11b) and then its left-hand first metal wheel shunts the first insulating fishplate (Fig. 11c). A momentary short-circuit occurs because of the opposite voltages of the adjacent rails, and the module turns to the “direct” mode, switching the polarity of the reverse loop so that it matches the through exit.

The polarity switch did not affect the locomotive, even though it happened right under her wheels, so she continues to roll around the reverse loop towards the diverging exit of the turnout (Fig. 11d-e). Of course, nothing happens when she shunts the second insulating fishplate because the polarities of the adjacent rails match. Then her right-hand first metal wheel shunts the third insulating fishplate, which produces another momentary short-circuit because the polarity of the reverse loop has been previously switched to match the through exit of the turnout. This triggers the module to turn to the mode “reverse”, which restores the match between the reverse loop and the diverging exit of the turnout (Fig. 11f). Once again, the DCC polarity switch did not affect the locomotive, so she entered the turnout by the diverging exit, pushing away the spring-loaded blades as she passed through (Fig. 11.g), and then she leaves the reverse loop, returning to the main line boiler first (Fig. 11h). So, the locomotive was successfully turned around without interruptions, abrupt stops, or any other incidents.

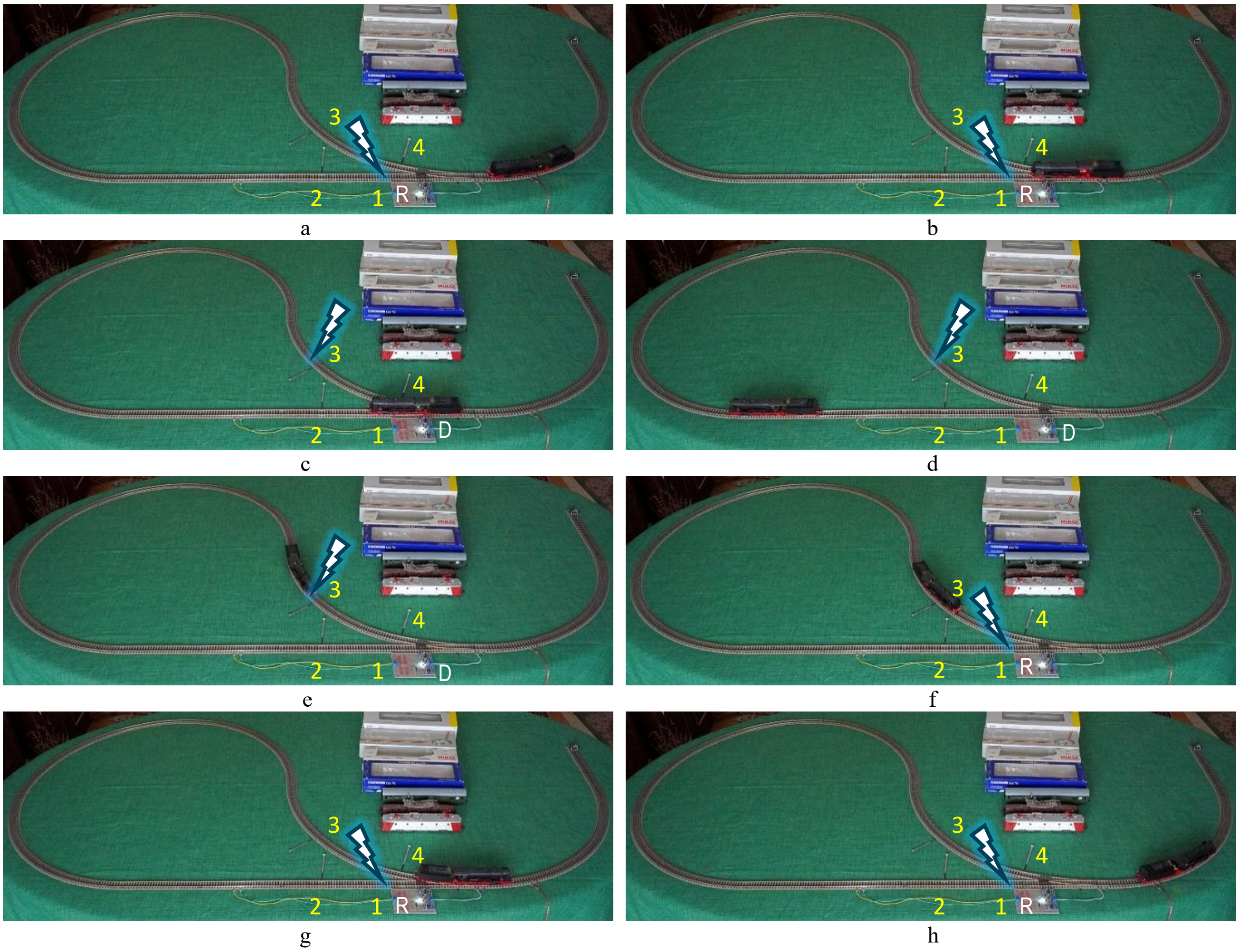

Fig. 11. Operation of the digital reverse loop module; the lightning sign shows polarity mismatch.

The second test was performed with the turnout spring-loaded blades set for the diverging exit, so now the reverse loop has been run in the opposite direction. As expected, everything went flawlessly.

Because of the momentary short-circuits, some random electric sparks were observed when the insulating fishplates were shunted by metal wheels, which did not affect at all the operation of the module and did not trigger the short-circuit protection of the central digital command station.

To reduce the occurrence of the above-mentioned momentary short-circuits, the polarity of the reverse loop should match the position of the turnout when a train arrives from the main line. This can be achieved by connecting the electromagnets of the turnout motor to the jumpers JP3 and JP4 (Fig. 7), with the common connection to the plus terminal of one jumper, and the connections for the through position and diverging position to the terminals that lead to the white SMD LEDs. Of course, antiparallel diodes must be used to protect the transistors. By choosing adequate values for the base resistors, the SMD NPN transistors T1 and T2 were able to handle both the driving commands for the optocouplers and the coils of the turnout motor, which are fitted with end-of-switching. Thus, the turnout is automatically set on the through position when the module is set on mode “direct”, and it is automatically set on the diverging position when the module is set on mode “reverse” (Fig. 12).

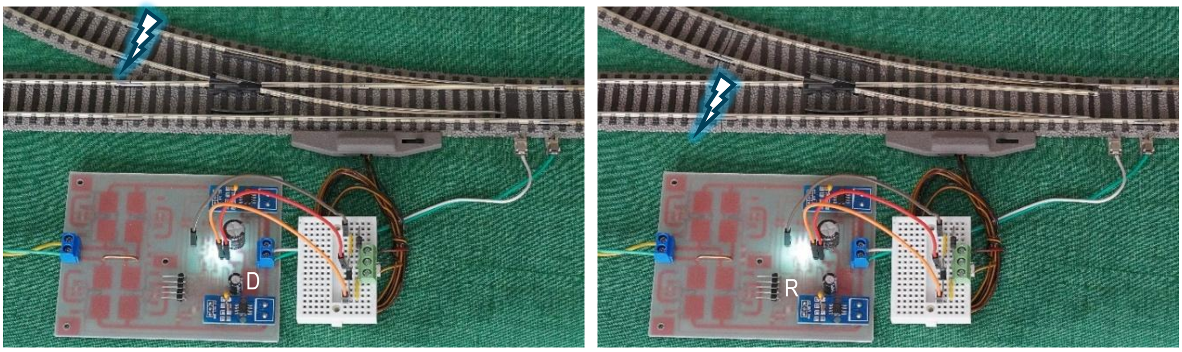

Fig. 12. Automatic setting for the turnout of the reverse loop.

Because this module is meant for the digital miniature layouts, the microcontroller program was upgraded with a digital accessory function. Thus, the module can also be driven by the central digital command station. With adequate sensors (optical, inductive etc.), the digital system acknowledges the position and direction of an incoming train that engages the reverse loop and sends commands to the module to set the correct polarity of the reverse loop without momentary short-circuits at all. Also, the module can be programmed and commanded directly by the user by means of the handheld controller of the central digital command station (Fig. 13).

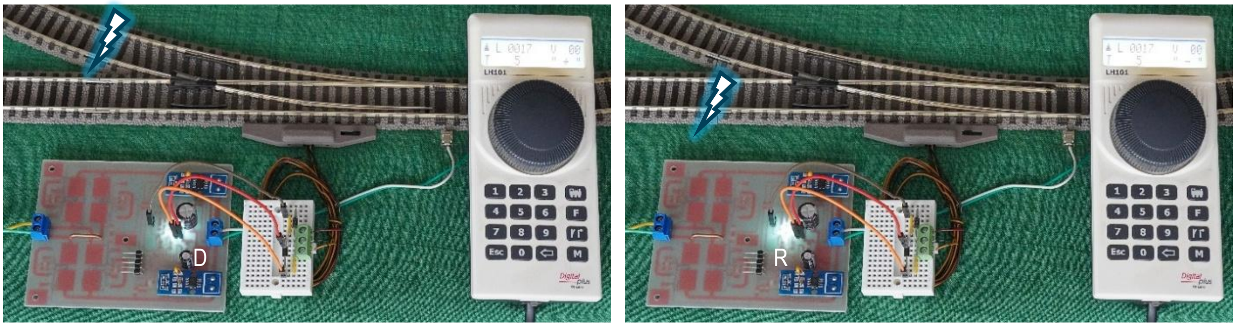

Fig. 13. Operation of the digital reverse loop module (address 5) by means of the central digital command station.

4. CONCLUSIONS

Model railroading is a very interesting and educational hobby that requires many skills, such as dexterity, attention to detail, thorough knowledge of fine mechanics, electronics, and computer science etc. If practiced correctly, it can provide learning of new notions, modelling, simulation, validation, development, relaxation etc. The small-scale replicas of the real trains must be handled with great care, both mechanically and electrically, and here the DCC system comes in handy, allowing the realistic and safe replication of the real-life train operations. This digital reverse loop module successfully joins a whole multitude of digital modules designed for miniature railway networks, bringing even more realism to their operation. This module proved to be suitable for use within any digital single-track reverse loops fitted with good-quality turnouts, with or without motors, allowing the automatic reverse of entire digital trains on the same railway line, provided they fit on the insulated portion of the reverse loop. Due to its features (digital accessory address, programming, feedback, automated turnout setting etc.), this module can be fully integrated into the DCC system of the entire digital railway layout, allowing extended degrees of automation and safe train operation.

Author contributions: The authors designed, built, and successfully tested this module according to the requirements and particularities of the DCC system. The authors programmed the microcontroller of the module according to the DCC standards [5], so that it can recognize and understand the DCC codes and react accordingly both to the DCC commands and to the present situations on the reverse loop itself. The authors studied and compared the features of already existing similar commercial modules, attaining added or improved features, such as response to DCC commands and sensors, programming, automatic switching of the turnout, the possibility of adding light signals etc. The hardware and software were checked and adjusted according to the test results. The automatic switching of the turnout and the operation of this single-track reverse loop can be applied for real-life railways, along with other already existing methods.
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Conflicts of Interest: There is no conflict of interest.

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