Automatic Real-time Control of Magnetic Field in an Optical Atomic Clock

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Summary - We present a compact device which is capable to automatically and in real-time controls the magnetic field in an optical atomic clock. The device is controlled via TTL signals and is programmed by the Ethernet during the experiment. ***Keywords—optical atomic clocks; automation; magnetic coils; trapped atoms; real-time***

I. INTRODUCTION

In an optical atomic clock the environmental perturbations affect the atomic transition frequency. The most dominant source of perturbations are the electromagnetic fields [1]. To compensate the frequency shifts due to magnetic field, a fine control over magnetic field coils is necessary, especially during the clock transition interrogation. The compensation is usually achieved by using the set of magnetic coils' pairs placed around atomic reference in all three directions. Typical manual control of the current in each pair of coils requires an operator involvement during calibration of the clock.

We present the design of a compact device capable of the real-time control of the current of coils automatically via TTL signals and the Ethernet during the clock operation. This device can be used for any kind of atomic clock and may be especially useful outside of the laboratory for portable and transportable clocks where the background magnetic field needs to be compensated more often [2–7].

II. METHODS/RESULTS

Precise control of magnetic field in cold atom experiment is necessary. For the Earth's magnetic field and any other magnetic fields in the laboratory, we need a 3D control to compensate. Three pairs of different Helmholtz coils usually ensure all these conditions. A schematic diagram of the working principle of device is shown in Fig. 1. The device can be controlled either from real-time or regular control computer and it applies currents directly to the coils. The magnetic field control device is able to tune the currents' values and change their directions independently for each pair. The in-clock-cycle control is done by TTL signals and additional settings can be transferred via the Ethernet from clock cycle to clock cycle.

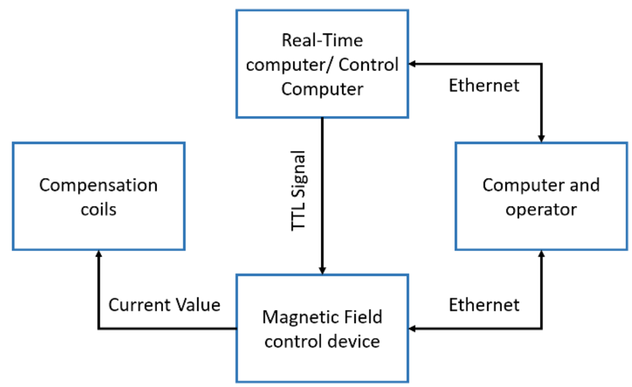

Fig. 1. Schematic diagram of the working principle of the controlling device.

Addressing and setting the output values is done by TTL signals (five addressing bits and one clock/set bit). The output in the range of -3 A to 3 A is provided by 16 bits digital-analogue converter stabilized to the ultrastable ADR443BRZ voltage reference. Also, current value would be applied by an arbitrary length linear ramp for avoiding shot noise in the system which can be programmed.

The picture of the controlling device is shown in Fig. 2. The device consists of a high-power electronic board and a microcontroller (NUCLEO-H743ZI2). A conceptual diagram is presented in Fig. 3. The full PCB schematics, and fabrication files for PCB design and manufacturing are available at [8].

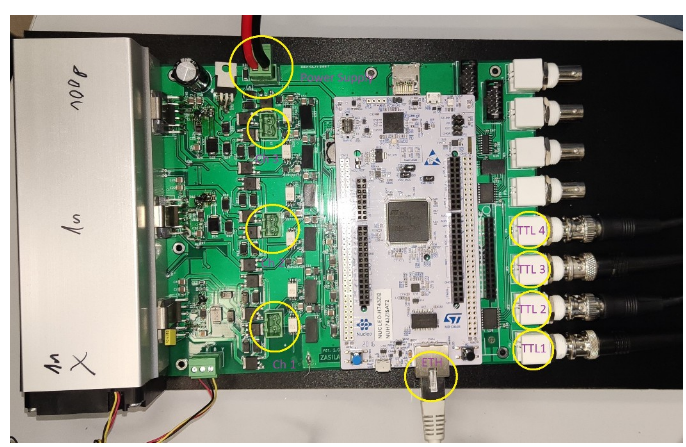

Fig. 2. Compact device.

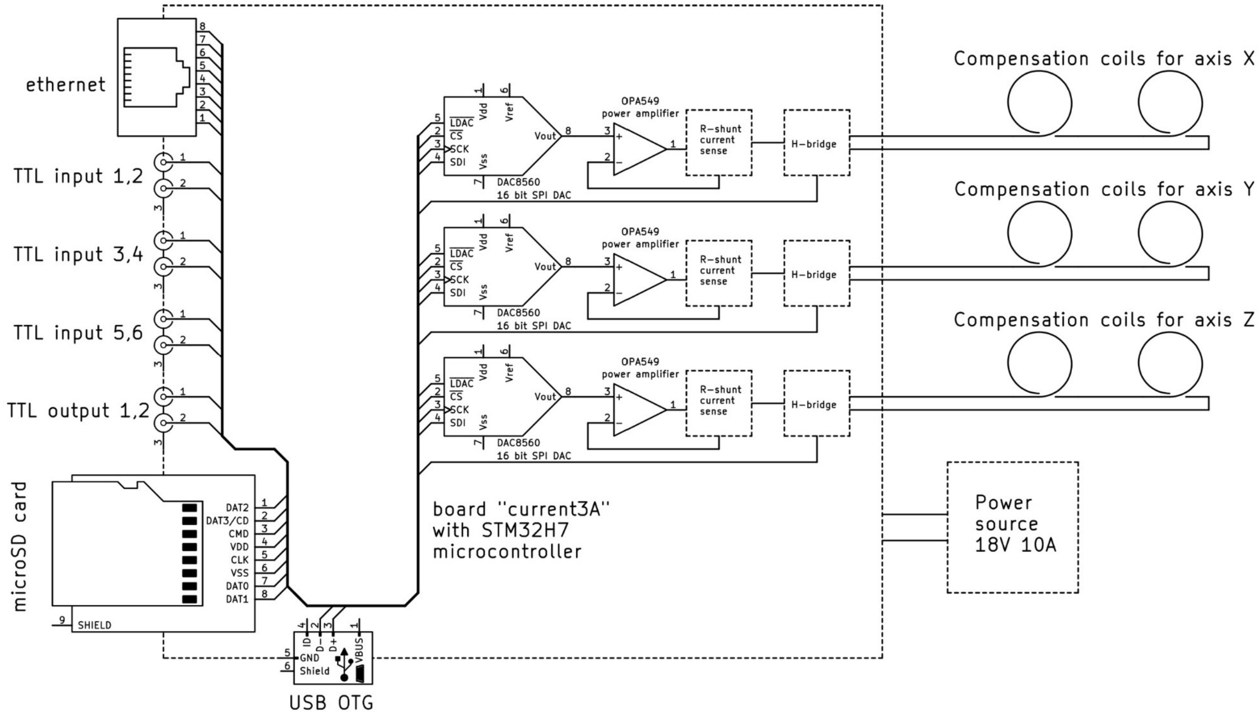

Fig. 3. Diagram of compensation coils controller.

For each channel, the current is stabilized to the digital-analogue converter output by sensing the current using high-quality shunt resistors. Coils are connected through a TTL controlled H-bridge. The value and direction of currents for each step of experiment is sent to the microcontroller via the Ethernet by a computer. The timestamps for applying currents are controlled by the TTL signals from a real-time computer. Moreover, this device can be programmed to perform automatic magnetic field compensation every given time. Additionally, different magnetic field values during different stages of atoms trapping may be used to optimize loading atoms into the optical lattice in optical lattice clocks.

For communicating with the compensation coils driver over telnet protocol, we provide an open source software that allows presetting up to eight values of the current, but it can be easily adapted to the full capabilities of the controller, including USB and microSD card inputs.

During operation, the output currents can be changed between preset values by input TTL signals. This method is compatible with digital input-out cards and real-time computers used in the laboratory environment to control experiments. Additional parameters stored in memory together with current values allows either fast switching between desired levels or a linear ramp of arbitrary time.

For pre-programming memory the format of command used in the telnet programming is:

< parameter address >: < value1 >; < value2 >; < value3 >; < time >

where “parameter address” choose the logical address in the memory, “valueX” are preset current values, and “time” is the length of a linear ramp in ms, value of 1 means the fastest possible switching.

Multiple parameters may be set with a single command by separating them with an “&” sign:

< parameter address >: < value1 >; < value2 >; < value3 >; < time >; & <address >: < value1 >; < value2 >; < value3 >; < time >; & ...

Two additional commands may used to get help and to close the connection:
help
exit

The most common parameters and addresses are presented in Table 1. After making a connection, if the connection is successful, a help message would be sent by the driver. This message guides the operator how to communicate with the driver.

Table 1. The most common parameters and addresses.

DAC: 000	Set values for memory 1
DAC: 001	Set values for memory 2
DAC: 010	Set values for memory 3
000	Address of memory 1
001	Address of memory 2
010	Address of memory 3

As an example, the command to pre-program the first two memory values is

DAC: 000: -1.25684; 0.5; 0.0; 1; & 001: 0.52; -2.1; -1.0; 50;

Switching to the first memory (000) levels takes 1 ms, while switching to the second memory levels (001) is made using a 50 ms long linear ramp.

In the current version of the software, switching between pre-programmed values is made by 4 TTL signals, but it can be easily expanded to use all 6 available TTL inputs. Three TTL signals address the required memory, and 1 TTL is a set/clock signal that triggers switching outputs to the new memory levels. TTL 1 is the least significant bit, and TTL 3 is the most significant bit.

For instance, the following pattern in Table 2 switches the controller output to the pre-programmed value stored in memory location 2 (001).

Table 2. pattern for switching to state 2 in memory location 2.

TTL 1	TTL 2	TTL 3	TTL 4
1	0	0	⎾⏋

We measured the efficency of the compact device after installing the magnetic field control device in the experiment of working passive optical atomic clock of our laboratory. This divece has been connected to a real-time computer and the following command is registered on the memory of microcontroller which is sent to it via the Ethernet by a computer:

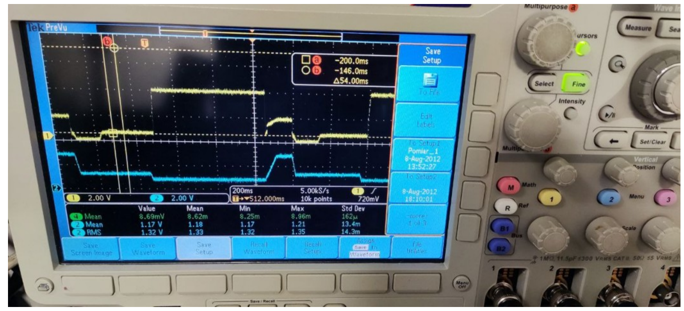

Fig. 4. Output of channel 3 in probe 2 on the compact device during experiment.

DAC: 000: 1.25; -1.8; 0.37; 10; & 001: -1.25; -0.8; 1.37; 60; & 010: 0.0; 0.0; 0.6; 20

There are three states in this command which they are applying in a specific time in each cycle of clocks, each state has three value which are for channel 1, 2, and 3 respectivly and time for linear ramp. The main program of working clock is running on the real-time computer and new state would be applied by microcontroller immediately after receiving set/clock signal by TTL as it shown in Fig. 4 for channel 3 or coils on Z axis, in this figure probe 1 is for main coils and probe 2 is output of the compact device for channel 3. Fig. 5 is same as Fig. 4 but for all channels which thire data have been exported from oscilloscope and data have been extracted for one cycle. As it is clear on the figure, changing values of compensation coils during each cycle of clock automaticaly is possible, and also new state is applied by a linear ramp, for example state 2 (001) is applied in 60 ms.

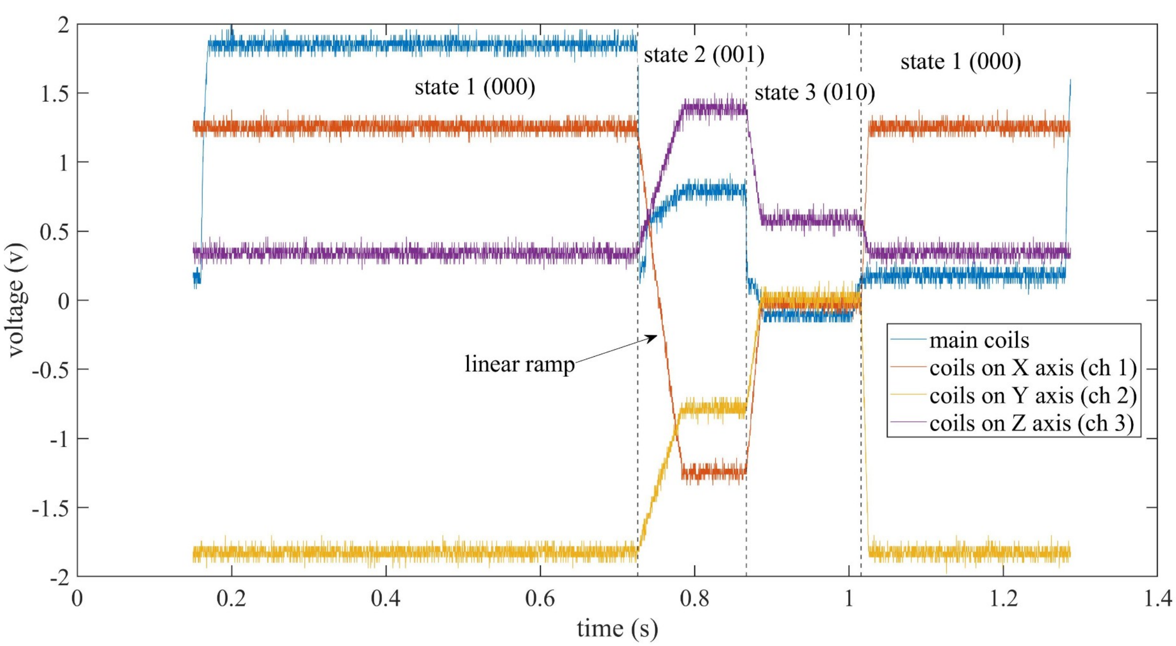

Fig. 5. Applied values from microcontroller in each cycle of clock.

III. Conclusions

We present a compact device for controlling automatically and in real-time the current of compensation coils for automatic control and calibration of magnetic field in any type of optical atomic clock. Also, we explained how to communicate with the driver via the Ethernet, and the result in real experiment of working passive optical atomic clock is shown how convenient is controlling over magnetic field during the experiment in each cycle of clock. This device is useful for atomic clocks and cold atom experiment which need changing magnetic field during experiment, and also for future active clocks.

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References

[1] A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, and P. O. Schmidt, “Optical atomic clocks,” Rev. Mod. Phys., vol. 87, no. 2, pp. 637–701, 2015.

[2] S. Origlia *et al.*, “Towards an optical clock for space: Compact, high-performance optical lattice clock based on bosonic atoms,” *Phys. Rev. A*, vol. 98, no. 5, pp. 1–11, 2018.

[3] L. Liu *et al.*, “Tests of Cold Atom Clock in Orbit,” Sep. 2017, Accessed: Dec. 20, 2021. [Online]. Available: http://arxiv.org/abs/1709.03256.

[4] M. P. Heß *et al.*, “The ACES mission: System development and test status,” *Acta Astronaut.*, vol. 69, no. 11–12, 2011.

[5] T. Lévèque *et al.*, “PHARAO laser source flight model: Design and performances,” *Rev. Sci. Instrum.*, vol. 86, no. 3, 2015.

[6] W. Wang, R. Dong, R. Wei, T. Chen, Q. Wang, and Y. Wang, “Compressing the fluctuation of the magnetic field by dynamic compensation,” *Rev. Sci. Instrum.*, vol. 89, no. 3, 2018.

[7] L. Li *et al.*, “Automatic compensation of magnetic field for a rubidium space cold atom clock,” *Chinese Phys. B*, vol. 25, no. 7, 2016.

[8] A. Ledziński and M. Zarei, “Compensation coils current controller (3x30A),” RepOD 2022. Available: https://doi.org/10.18150/YHSPTP.