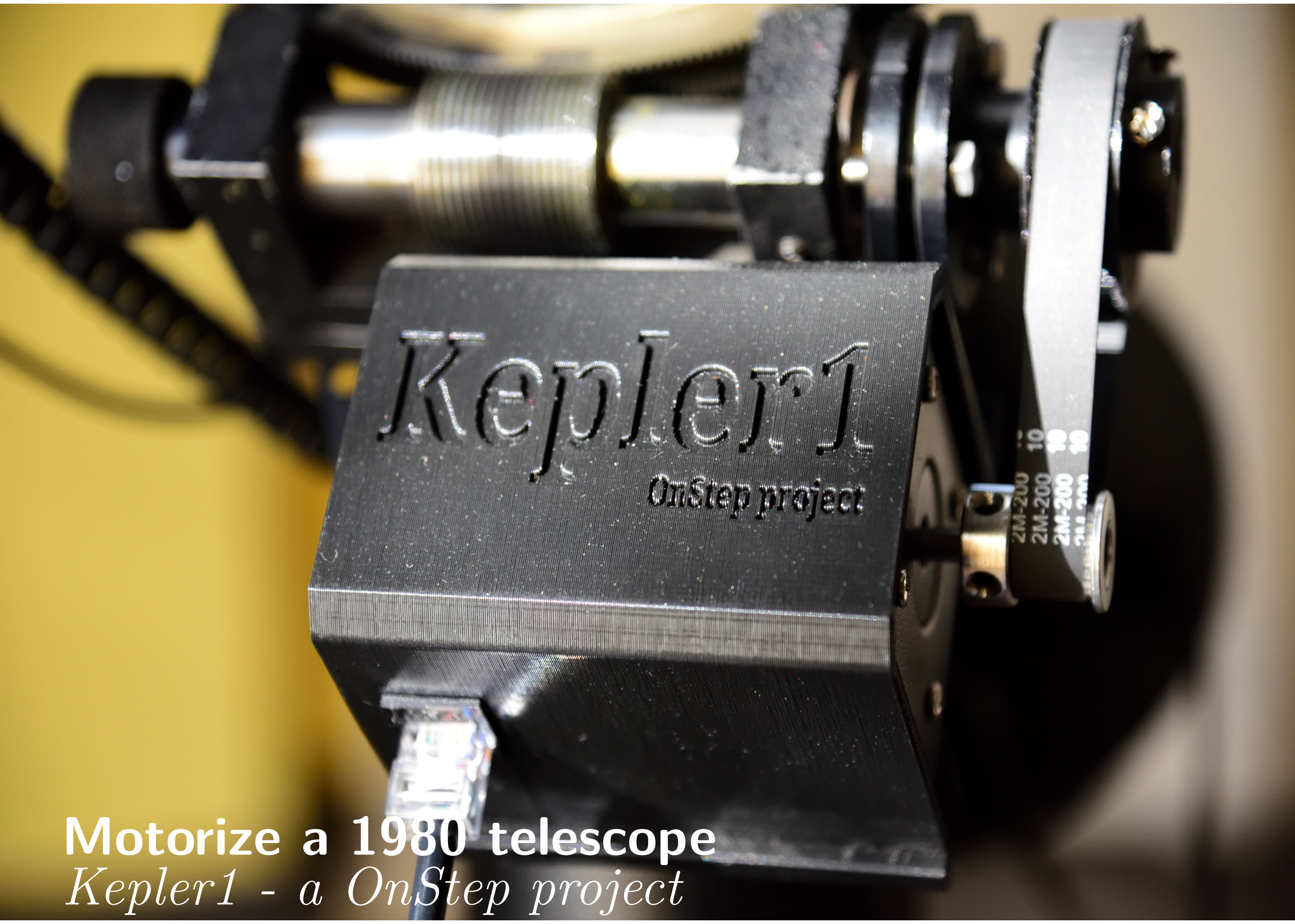

Motorize a 1980 telescope

Kepler1 - a OnStep project

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Abstract

A 1980 (old and dusty) fork equatorial telescope is converted to an up-to-date, motorized and computer-connected telescope. We illustrate all the transformation steps from an old, dusty and unused telescope into an optimal tool for astrophotography.

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Contents

Introduction

The Kepler1 project led to the developing of a telescope mount with right ascension (RA), declination (DEC) and focuser (FOC) movements fully motorized and controlled by the software OnStep with a precision well below $1''$ in both RA and DEC mechanism starting from a 1980 telescope. The final setup components are reported in section 7, go there to find out our conclusions.

In section 1 we describe the starting telescope mount, the substitution of the old telescope tube with a new one and the installation of the latter.

In section 2 we show the electronics we have used; starting from the ESP32 board WeMos D1 R32 with CNC3 shield we describe the motor drivers, the components for the WiFi connection, the time clock and the weather sensors. We also describe some modification to the CNC3 shield to improve the microstepping control with gotos.

In section 3 we have constructed the mechanisms for the RA movement, some versions of the DEC movements and the FOC motorization.

In section 4 we explain how to cleverly attach and detach the motors on the main board using ethernet cables.

In section 5 we explain the basics of the software OnStep and some additional apps that we use for the tracking (*i.e.* PHD2) and Stellarium.

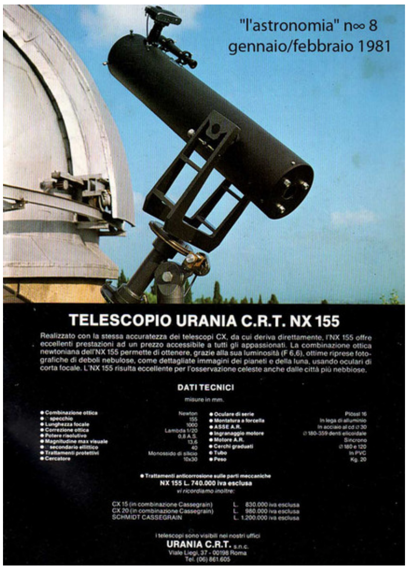
In section 6 we briefly show the tracking system and some tests operated with the mount with the results.

The result of our work is the telescope in figure 1.

Figure 1: Final result: our brand-new telescope.

1 Telescope description

The starting point of the project is of course the telescope. In our garage, for many years, a 1980 Urania telescope has eaten a lot of dust. The telescope's mirror resent of years in humidity and temperature jumps in the garage. In the beginning, we have cleaned the silvered-mirror with soap and water, but the silver still seemed to be a bit compromised. We do not talk long about this telescope, since we have soon substituted it with a brand-new Skywatcher Quattro. The latter is placed on the Urania mount, since it is still a nice mount and, in our advice, has still not surpassed robustness. Indeed, the mount is a very heavy (telescope and mount totally weight 20kg!) equatorial and motorized (still works!) mount.



(a) *Urania telescope and mount.*

(b) *Skywatcher Quattro telescope.*

(c) *The mechanism built to insert Skywatcher's telescope into the Urania robust mount.*

Figure 2: The transition between the old telescope to the new telescope: (a) the starting point telescope, (b) the new telescope, (c) and (d) the telescope seat used for the substitution.

For our money, but most importantly for our fun and entertainment, we decided to modernize our old telescope.

1.1 Urania telescope

We briefly add the specifics of the old Urania telescope, as a sort of respect for many years of honorable work before the deep dark in the garage.

The telescope is a Urania C.R.T. NX 155, as the one in figure 2a.

Specific's name	value
type	reflector
technique	Newton
material	PVC
weight (kg)	10
aperture (mm)	155
focal length (mm)	1000
focal	f/6.5
resolution power	0.8
limit magnitude value (mag)	13.6
Mirror Treatment	Silica monoxide

Table 1: Urania C.R.T. NX 155 specifics.

1.2 Telescope's mount

The telescope is place onto an aeronautic Aluminum tripod equatorial mount.

Specific's name	value
weight (kg)	25kg
type	fork
material	Aluminum alloy
RA axis diameter (mm)	30
RA axis material	cadmium steel
RA motor	3W synchronous

Table 2: Urania's mount specifics.

Starting from the bottom: three pods of 45cm depart from a central post. Each one has a wheel which permits the structure to move freely and then to fix the position using stops. The central post terminates with the second axis holder whose inclination can be adjusted using a big screw. Using a digital inclinometer we fix the axis to be at $45.75'$ with respect to the ground.

This axis must be aligned with the Polar star (labelling the North). In this way, a 3W synchronous motor can follow the sky movement.

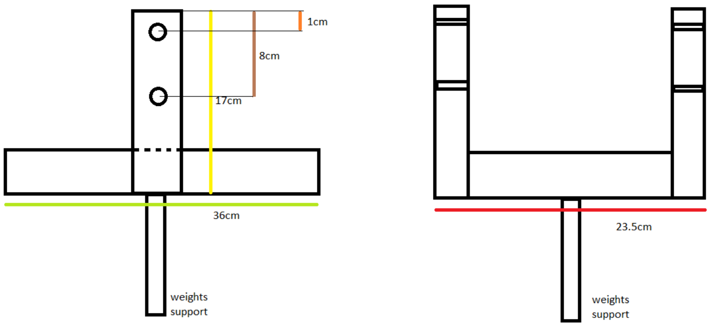
Departing from this second axis, a two-arms fork is free to rotate around two degrees-of-freedom defining the right ascension (RA) and the declination (DEC). The two arms are separated by the distance $d = 260$mm which is enough to fit the Urania telescope aperture.

1.3 Skywatcher 8P Quattro telescope

Skywatcher 8P Quattro Newtonian telescope (figure 2b) offers an optimal astrophotography performance. For this reason we have decided to substitute the Urania telescope with this brand-new Skywatcher telescope.

(a) *Internal bearing mounted on one fork arm.*

(b) *External bearing mounted on one fork arm.*



(c) *Schematic view of the telescope mount insertion. This represents only the installation build with some squared metal bars upon which the two white loops (which hold the telescope tube) are fixed and are not illustrated in this scheme. The two holes in each arm serve to fix the structure on the mount.*

Figure 3: Telescope seat details.

Specific's name	value
type	reflector
technique	Newton
material	Carbon
weight (kg)	8.0
aperture (mm)	200
focal length (mm)	800
focal	f/4
resolution power	0.58
limit magnitude (mag)	13.3
collect light	820
magnification	400
Mirror Treatment	Aluminum Coating
Focuser	Crayford dual-speed 50.8/31.8

Table 3: Skywatcher 8P Quattro

Since the Skywatcher telescope does not fit in the fork, we have thought to build a "saddle" onto which placing the telescope. The specifics of this installation are shown in the following section.

1.4 Telescope substitution: from Urania's tube to Skywatcher's tube

Passing from the Urania telescope to Skywatcher telescope we have faced the problem of how to insert the latter in the telescope mount. Indeed, since Skywatcher's telescope diameter is 200mm it does not fit inside the mount fork.

Our solution is to insert a seat in which to place the telescope, see figure 2c. The barycenter of the telescope is not centered with the DEC axis, thus we have settled a post capable of holding weights to balance the forces, see figure 3c.

The scheme with distances is visible in figure 3c.

Lastly, to enhance the fluidity of motion and reduce the backlash, the rotation mechanism is enriched with a system of two bearings for each fork arm, one is place inside, see figure 3a, and one is fixed externally on the mount, see figure 3b.

The total weight of the mount with this modification is attested on 30kg.

2 Electronics

The circuit design is represented in figure 4c. In this section we expose the electronic components used in the circuit.

2.1 ESP32

ESP32 is a series of low-cost, low-power system on a chip microcontroller with integrated Wi-Fi and dual-mode Bluetooth. We've bought the ESP32 D1 R32, the one in figure 4a, for better attaching the motor using the CNC shield V3 (which is briefly explained in the following).

We decided to follow the "WeMos R32 and CNC V3" OnStep project (at `https://onstep.groups.io/g/main/wiki/19670`). OnStep is an open source software providing the control of four stepper motors (RA, DEC, focuser and rotator for astrophotography), weather sensor handling, Wi-Fi and Bluetooth connection, polar alignment and other nice features.

2.2 CNC Shield V3

To better optimize space and wires connections, we have bought a CNC Shield V3 (a.k.a. CNC3), see figure 4b.

It is a printed circuit board (PCB) built for 3D printers. The shield is attached directly above the ESP32. It has four slots, each one can host a motor driver, thus using this shield there can be handled four stepper motors: RA and DEC motors, first focuser and photography rotator or second focuser.

This shield can be "manipulated" to obtain better performances.

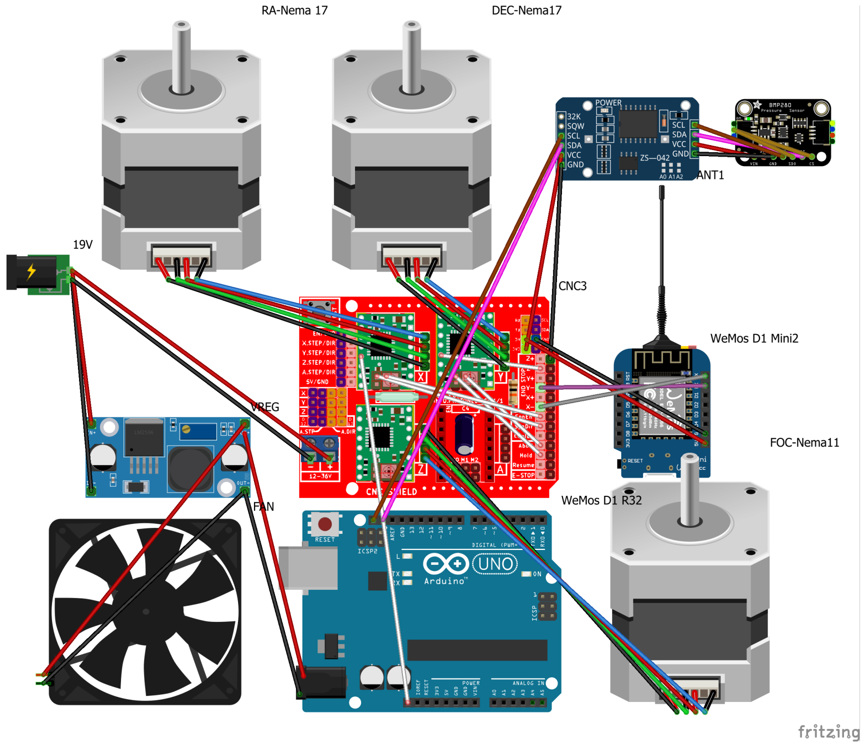
2.3 Motor drivers

A stepper motors works only with a driver chip that controls the motor movements. Three types of drivers have been used during the configuration of the setup.

1. DRV8825;
2. TMC2209;
3. TMC2208.

(a) ESP32 D1 R32 picture.

(b) CNC3 Shield V3.



(c) Circuit design. Here can be found the png file.

Figure 4: Main board components: (a) WeMos D1 R32 ESP32 board, (b) CNC shield V3 and (c) the circuit design: the Arduino board is instead a ESP32 board, like the one of figure (a); the white cables are our modifications on the board.

In each driver the right amount of current is set, otherwise the stepper motor could work improperly. This current depends on the stepper motor current per phase parameter. Typically, drivers have a tunable screw for the tension V_{ref}. For each type of driver, the formula to calculate the tension V_{ref} depending on the current/phase are different.[1]

The procedure is the following:

- rotate the screw in the counter clock direction;
- using a multimeter, check that the tension is zero;
- slightly rotate the screw until the tension is the desired one.

We recommend reducing the theoretical value by a 10%-30% to prevent motor dangers.

2.3.1 DRV8825

For these drivers the tension to be set is roughly the half of the value of the nominal current/phase of the motor. For example, if the motor has a current/phase 1A, the tension would be 0.5V.

Current phaser (A)	Current (A)
0.90	0.45
2.00	0.90

Table 4: DRV8828 drivers setup current. Note that we have set a value smaller than the one calculated to prevent motor to break.

[1] See this for more details.

2.3.2 TMC2208 and TMC2209

For these drivers the tension value is roughly the same of the current/phase value, *e.g.* if $I = 1$A the tension would be $V_{ref} = 1$V. Be aware that the TMC2208 has a maximum current output of 1.2A.

The calculation is

$$\frac{I}{\sqrt{2}} = \frac{325mV}{110m\Omega + 20m\Omega} \cdot \frac{1}{\sqrt{2}} \cdot \frac{V_{ref}}{2.5V} \Rightarrow V_{ref} = I \cdot 1\Omega.$$

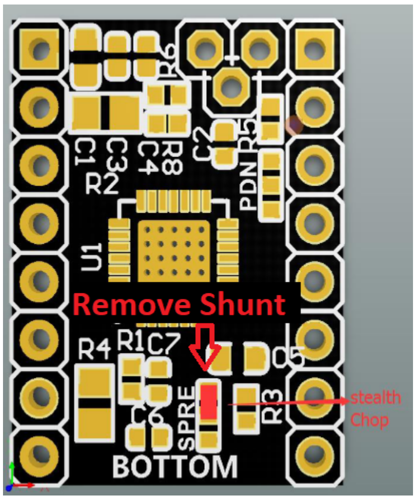
Remember to reduce to value by a 10%-30%.

Driver	Current/phase (A)	Current (A)
TMC2208	0.90	0.81
TMC2208	2.00	1.63
TMC2209 (focuser)	0.67	0.50

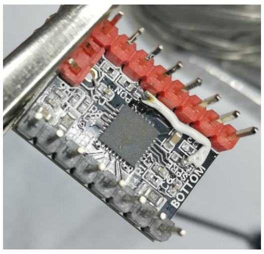
Table 5: DRV8825 drivers setup current. Note that we have set a value smaller than the one calculated to prevent motor to break.

2.4 CNC3 and TMC2209 modifications

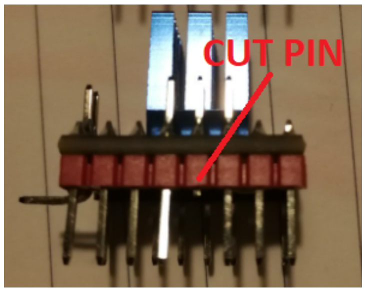
CNC3 shield does non permit "on the fly" change of microstepping since they are achieved via the MS0/MS1/MS2 fixed jumpers below the motor drivers. This means that you cannot have different microstepping for tracking and slewing unless you use TMC2130 or TMC5160 through SPI interface. To overcome this CNC3 limit when using other drivers (*e.g.* TMC2209 that are very silent, guarantee a 2A current per phase and are somehow cheap), it is necessary to do some soldering on the CNC3 and the TMC2209 and modify the pinmap "Pins.CNC3.h".



(a) TMC2209 driver with highlighted modifications.



(b) Connection of the Spread pin to pin 5 by wire.



(c) Cut low pin 5.

Figure 5: TMC2209 modifications.

2.4.1 Microsteps control

First of all it is necessary to configure the TM2209 stepper driver (TMC2209 Bigtreetech v1.2) to remove the Spread shunt (that controls StealthChop vs SpreadCycle mode) on the TMC2209 board and then wire connect the Spread to pin 5 of J1, see figures 5a 5b.

Finally, you have to cut the low pin 5 of J1 on the TMC2209 driver since it is shortcutted with pin 6 (CLK) on the CNC3, see figure 5c.

At this point, we have a wire connected (some soldering) the MS0 and MS1 of Axis X to the SpnEn and SpnDir pins of CNC3 respectively. In the same way, we have a wire that connected the MS0 and MS1 of Axis Y to the HOLD and ABORT pins respectively. In this way, we are able, after modifying the pinmap in "Pins.CNC3.h" to control the microstepping in Tracking and Goto both in RA and DEC. You can find the modified Pinmap "Pins.CNC3.h" here.

The last modification is simply to connect with a wire jumper pin 5 of TMC2209 of AXIS X to the pin IO0 of the WeMos D1 R32 as well as connect pin 5 of TMC2209 of AXIS Y to the pin Z− of the CNC3. With this done we able to set programmatically (via Config.h) the SpreadCycle (StealthChop) mode using the TMC2209_QUIET (TMC2209_VQUIET) constants.

Here is the updated "Config.h".

2.5 Power supply

The power supply is provided by a 19V 5A power supply as in table 6.

voltage output (V)	current output (A)
19.3	4.74

Table 6: Nominal tension and current outputs of the power supply.

For our initial purposes it was enough, indeed 5A are enough to feed quite well two stepper motors and a poor electronics. A rough estimation poses 1.8A for DEC motor, 0.9A for RA motor and few milliampéres for the ESP32. The reader is strongly encouraged to check the total current its circuit needs before buying a power supply.

To provide the 3.3V tension to the microcontroller, a IC-QUANZX voltage regulator is place between the power supply and the ESP32.

2.6 Sensors: WiFi connection, Real time clock (RTC) and weather sensor (BMP280)

OnStep contains the so-called Smart Web Server (SWS) that provides WiFi (or Ethernet) connections using an IP but it does not exploit the native ESP32 chip for the WiFi connection; To command the mount via WiFi a ESP8688 WeMos D1 mini must be connected to the CNC3.[2] Many devices support this type of connection including cell-phones, tablets, laptop/desktop computers, etc. Using this library, it is possible to use programs such as Stellarium via ASCOM drivers provided by the OnStep project. We have added an antenna to enhance the WiFi connection range.[3]

The weather sensor BMP280 is modified as follows: the CSB and the SDO pins are connected directly to the Vcc. The sensor is then attached directly to the RTC module Ds3231.

The RTC, BMP280, the WiFi module and the stepper motors are connected to the WeMos ESP32 D1 R32+CNC3 board as in figure 4c.

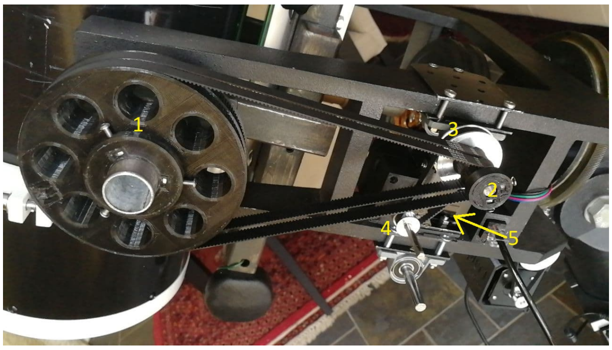
3 Mechanization

The motorization of the telescope passes through two mechanics adjustments:

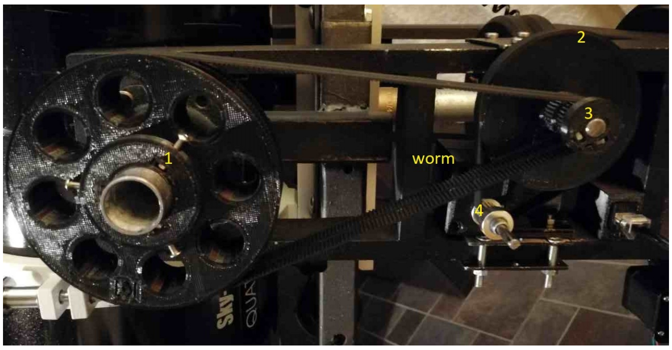
1. motorize the RA movement, exploiting the native tracker mechanism;
2. motorize the DEC movement, which natively has no gears.

Before entering in the details, we define the stepper motors used in the setup.

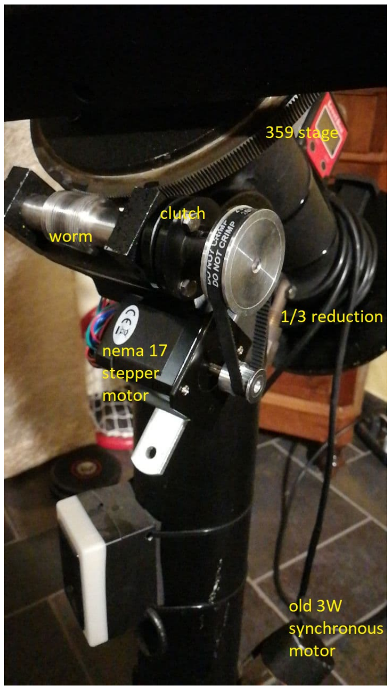
[2] For the pinout maps look at this connection diagram.
[3] Take a look at this to see how to do that.



(a) DEC V1 mechanism.



(a) DEC V1+ mechanism.



(b) RA mechanism.

Figure 6: RA and two of the many versions of the DEC mechanization.

3.1 Stepper motors

In this subsection we write the specifics of the stepper motors used for the RA and DEC mechanization (for both we have used nema 17 motors) and the focuser (developed with a nema 11 stepper motor).

3.2 RA motorization

The telescope's mount has already a tracking mechanism motorized by a 3W synchronous motor. So, in principle, it is only a matter of substitute this old motor, with a new programmable stepper motor.

The gears are composed by:

- a 359 teeth stage (1 tooth for each degree, fantastic);
- an endless screw (worm) mounted on a shaft through a clutch.

Using this structure, for a continuous sky tracking, the elder motor would complete a round of the worm in 4 minutes. Thus, this mechanism rotates the mount with the velocity of a degree in 4 minutes (which is the velocity of the sky moving away in the night).

We have reduced the ratio by a third adding two other gears (see figure 6b): 60 teeth gear positioned in the shaft and a 20 teeth gear on the motor shaft.

ratio gear 1	**ratio gear 2**	total **ratio**
1/360	1/3	1/1080

Table 7: Total reduction of RA mechanization.

We have chosen to install a nema 17 stepper motor with the specifics in table 15

3.3 DEC motorization

The mechanization of the DEC axis was a bit more complicated since there was not a built-in gear to use. We tried different versions. A first successfully try was to exploit a stand-alone disk. On the edge of the latter are present some ticks and grades: it was used a declination angle teller.

As told above, we have tried different configurations, but same stepper motor is used.

3.3.1 DEC V1

Using a 3D printer we have designed a double-belt gear. Then, a 1/10 ratio is obtained using a worm gear and another 1/3 is obtained between the worm and the final gear. The total reduction with all gear specifics is reported in table 8. Figure 6a is a picture of the mechanism. The precision of the mechanism is

$$\delta_{th.} = 0.28'', \quad \delta_{est.} = 0.96''$$

where *th.* stands for theoretical and *est.* stands for estimated.

DEC-V1 stages

Gear number	1	2	3	4	worm
number of teeth	180	30	60	20	10
total ratio	$\sim \frac{1}{180}$				

Table 8: DEC mechanism's gear specifics.

3.3.2 DEC V1+

Starting from the DEC V1, we have designed a new gear to get a bigger reduction ratio (this is the reason for the +). The total reduction with all gear specifics is reported in table 9. Figure 6a is a picture of the mechanism. The precision of the mechanism is

$$\delta_{th.} = 0.14'', \quad \delta_{est.} = 0.48''$$

where *th.* stands for theoretical and *est.* stands for estimated.

DEC-V1+ stages

Gear number	1	2	3	4	worm
number of teeth	180	30	120	20	10
total ratio	$\sim \frac{1}{360}$				

Table 9: DEC mechanism's gear specifics.

3.4 Focuser motorization

Another improvement is the motorization of the focuser. Using a nema 11 stepper motor, we have created the motor supports and the gears using a 3D printer. The reduction stage is 1/3, and the mechanism is visible in figure 7c.

4 Cable management

The wiring between the electronics and the motors is made focusing on the main idea to attach and detach them rapidly. We thought to use Ethernet cables. They are a versatile solution but how to connect them to the four cables governing the stepper motor?

Stepper motors have four cables, see figure 8, which have to be driven to the CNC3.

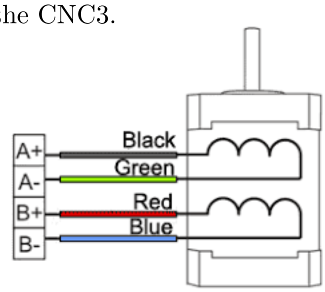


Figure 8: Stepper motor cables scheme.

4.1 Ethernet cables

Ethernet cables are composed typically by 8 thin cables, each one carrying very few Amperes, approximately $0.3 - 0.5A$. Since stepper motors require currents of the order of $1A$, we decided to use them in couple, according to the general Ethernet cabling scheme. Thus, the four motor cables are doubled and fixed into the eight way Ethernet socket.

Then, the main box is prepared to receive the Ethernet cables. In the most remote drawers of the garage, we have found an old and burned electronic card with four Ethernet sockets, a power supply entry and an on/off switch. Using a multimeter we have checked the pins of each slot and created the connections to the CNC3 shield.

In figures 7a, 7b and 7c are shown some examples of Ethernet wiring.

4.2 Plastic boxes

Using a 3D printer, we have created the focuser motor box with the Ethernet exit, and so we did for the RA motor. The microcontroller, the CNC3 shield, the power supply and all the electronics have been thrown in a box. The stepper motors drivers after a while become very hot, then we have decided to put a fan in the box. In figures 7a, 7b and 7c are shown the resulting plastic boxes.

5 The software

Now comes the software part. In our mind, we wouldn't want to spend much time on programming. We desired a plug-and-play solution, or something similar. A software with easily controlling and possibly which can talk via ASCOM drivers with Stellarium (or others), PHD2 and others astrophotography programs.

5.1 OnStep

On the internet, we have found a great, open-source, free and customizable software called OnStep.[4] We have followed the instructions for the WeMos D1 + CNC V3 project, configured the Config.h file and upload the sketch on the ESP32 board.

Finally, the box is placed on the mount and connected with the Ethernet cables to the motors

5.2 PHD2

Push It Dummy-2 (PHD2) is the software that controller the auto-guiding system. PHD2 is telescope guiding software that simplifies the process of tracking a guide star, letting you concentrate on other aspects of deep-sky imaging. There are plenty tutorials on the internet showing how to use PHD2, so we do not enter so much into details.[5] But we only want to stress out that, after few important configuration passes, the auto-guiding is really simple and promises very good results!

5.2.1 Wizard configuration

Connection is really simple using the "wizard" option suggested in every tutorials. The "unbinned pixel size" is one of the first parameters you have to fix in the wizard which are not quite clear. You should be able to get the unbinned pixel size from the camera spec sheet or the manufacturer's web site. If this is not the case, you can get the unbinned pixel size by taking the dimension of the sensor and diving it by the number of pixels.

The "bin level" is the technique to combine proximal bins to form a "superpixel".[6] This has the effect of reducing the noise but at the price of reducing the image definition.

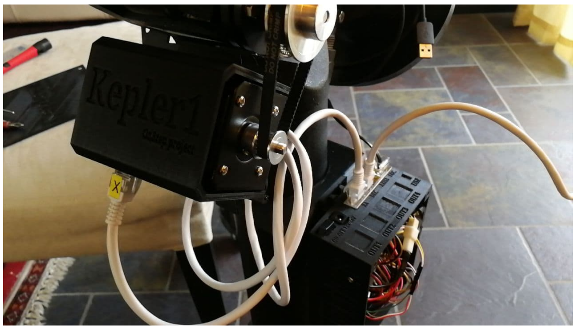
Another remarkable option to fill is the telescope mount's driver, which in this case are the ASCOM OnStep telescope drivers.

[4] Wiki groups:https://onstep.groups.io/g/main/wiki/3860. Github:https://github.com/hjd1964/OnStep.

[5] https://www.youtube.com/watch?v=Kd4qzW7uV38 or the pdf https://openphdguiding.org/man-dev/Basic_use.htm.

[6] https://www.photometrics.com/learn/imaging-topics/binning-2.

(a) The main box containing the electronics and its easy management Ethernet connections.



(b) The RA motor box containing the stepper motor and its Ethernet socket.

(c) The focuser box containing the focuser stepper motor and its Ethernet socket.

Figure 7: Plastic boxes.

5.2.2 Dark libraries

Before starting the first guiding session, it is useful to spend 5 minutes to create a dark library. To do so, just press the "Dark" tool on the top and create a new dark library. Cover the guidescope, and start the acquisition.

After the acquisition, remove the cover; this should make clearer acquisitions.

5.2.3 Connect all!

After the configuration, press the first icon in the bottom left and press "connect all". Now the camera and the mount are connected to PHD2.

5.2.4 Calibration

Search a bright star whose declination is between 10 to -10 degrees. Start the acquisition pressing the "cycle" icon (the second from the left), then press the "star with a magnifying glass" that selects the most bright star. Finally, push the PHD2 icon; this will start the calibration and requires few minutes.

5.2.5 Guiding

If dark libraries and calibration are done, the guiding can start. If it is not present, search in the settings the plot visualization that let you know the adjustments that PHD2 is doing. In our case, it is a useful tool to see if our work were precisely enough.

A useful tool is the "use multiple stars" in the guiding settings. The latter permits holding multiple star, and we think this is another improvement to stability in auto-guiding.

5.3 Stellarium

Stellarium is the software we use to search objects. The impressive feature is that, after paring it via ASCOM drivers with the mount, it is possible to tell the telescope to move at the star pointed out in Stellarium.[7]

The telescope is now free to start few tests to check the goodness of our work!

6 Tests

The test are aimed to estimate the precision of the mount. Of particular interest are the test using PHD2 which measure the precision in micro-adjustments for the auto-guiding system.

The application used to study the PHD2 plots is the PHD2LogViewer app. The latter can upload all the guiding session you make, since every session is stored in the PHD2 folder. The app also make raw statistical analysis which are good parameters to think about. The root-mean-square (RMS) describe the spread of the data points around some average peak value (like standard deviation). The value of RMS should be 1 arcsecond or lower for a good guiding.

Before describing the tests, let us show the tracking system, which is composed of a guidescope and a tracking camera.

6.1 Telescope guidescope

On the telescope is fixed a 240mm focal length guidescope Svbony SV106.

6.2 Guidescope camera

The camera is an old red webcam inserted into the guidescope using an adpter.[8] The result is pretty weird, but it works! Just look at the following sections PHD2 logs!

[7] See https://www.youtube.com/watch?v=DUdYv311HFw.
[8] See this useful tutorial https://telescopeguides.com/how-to-use-a-webcam-with-a-telescope/.

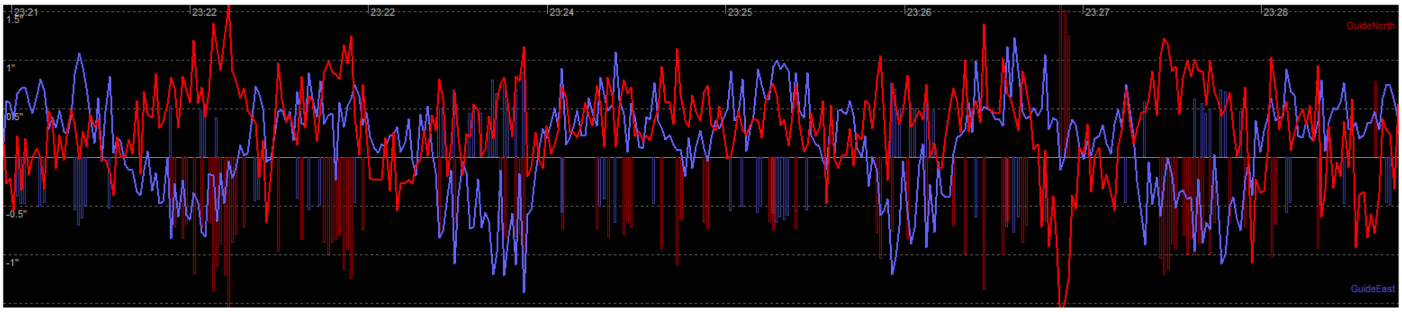


Figure 9: DEC V1 test: PHD2 log view using arcseconds as units. In pixel the scale is in the range $[-0.4, 0.4]$. The sky seeing was $0.98''$.

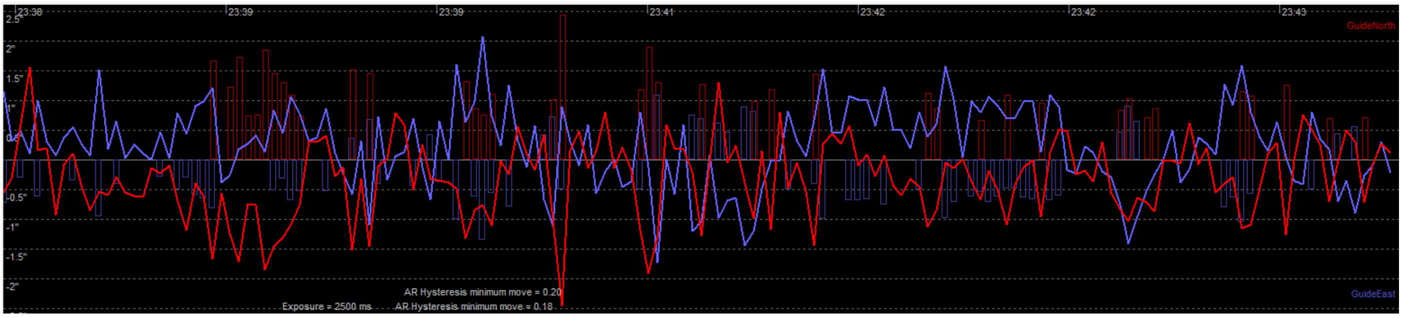


Figure 10: DEC V1+ test: PHD2 log view using arcseconds as units. In pixel the scale is in the range $[-0.5, 0.75]$. The sky seeing was $1.80''$.

6.3 DEC V1 test

The DEC V1 has been developed to reduce the mechanism backlash using the idea *the less the number of belts gets, the better the guiding is.* The resolution power of the mount is reported in table 10. The extrapolated statistics is reported in table 11.

Mechanism	microsteps (x360°)	estimated resolution (”)
RA	19200	0.21
DEC	12800	0.65

Table 10: Resolution power using the DEC V1 mechanism. Microsteps is intended as the total number of microsteps around the entire circumference.

After the calibration, we have pointed the Rosetta nebula and start tracking. The result can be seen in figure 9. The sky condition was very nice that night with a seeing of $0.98''$.

Statistics	RMS	Peak
RA	0.47" (0.15 px)	1.87" (0.58 px)
DEC	0.90" (0.28 px)	-8.12" (-2.52 px)
Total	1.02" (0.32 px)	

Drift	("/min)	(px/min)
RA	+3.01"/min	+0.94 px/min
Dec	+2.14"/min	+0.66 px/min
Polar Alignment Error	8.7’	

Table 11: DEC V1 test: statistics of the guiding of figure 9.

6.4 DEC V1+ test

We have updated the DEC V1 mechanism to DEC V1+ to introduce a more gear reduction and the possibility to decouple the telescope movement from the gear to perfectly balance it. The resolution power of the mount is reported in table 12. The extrapolated statistics is reported in table 13.

Mechanism	microsteps (x360°)	estimated resolution (”)
RA	51058	0.24
DEC	25600	0.48

Table 12: Resolution power using the DEC V1+ mechanism. Microsteps is intended as the total number of microsteps around the entire circumference.

After the calibration, we have pointed Aldebaran and start tracking. The result can be seen in figure **??**. We point out that the sky condition was not optimal since the seeing was $1.80''$. The latter parameter effect with spurious drifts the guiding.

Statistics	RMS	Peak
RA	0.66" (0.20 px)	-2.04" (-0.63 px)
DEC	0.63" (0.20 px)	-2.40" (-0.75 px)
Total	0.91" (0.28 px)	

Drift	("/min)	(px/min)
RA	+3.39"/min	+1.05 px/min
Dec	-3.65"/min	-1.13 px/min
Polar Alignment Error	14.5’	

Table 13: DEC V1+ test: statistics of the guiding.

7 Conclusion

After lots of hours testing our telescope, we can declare what is the best configuration found using the WeMos D1 + CNC3 shield.

Part	component
Microcontroller	WeMos D1 R32 (ESP32)
Pinmap	CNC3
Voltage regulator	5V
Time	RTC DS3231
Weather sensor	BMP280
WiFi	ESP8688 WeMos D1 mini
RA stepper motor	17HM19-2004S1 (2.0A)
RA motor driver	TMC2209
RA cable	microphone 8 poles cables
DEC stepper motor	17HM15-0904S (0.9A)
DEC motor driver	TMC2209
DEC cable	microphone 8 poles cables
FOC stepper motor	11HS12-0674S
FOC motor driver	TMC2208
FOC cable	8 poles cable

Table 14: Final setup parts and components.

In table 14 we report the components used for the last test, which is the best result we obtained in terms of guiding and in terms of resolution in table 12. We also show our impressions on the various components tested.

The best drivers are the TMC2209. They are the most silent, the most quick and precise. They are used in our setup for the RA and DEC motors. Otherwise, for the focuser the TMC2208 driver has been used.

The best stepper motor is the 17HM19-2004S1 for its superior precision and power, and we have used it in the RA mechanization because of its robustness at high speeds. It is worth noticing that the most used one in others project is the 17HM15-0904S stepper motor. We have tested it both in the DEC and the RA mechanization, and it does its own work; we have used it in the DEC mechanization because in this mechanism we do not require a lot of torque as in the RA mechanism.

Onstep software has always lived up to expectations. Its existence has allowed us to focus on hardware development and not worry about the software side. In addition, the OnStep ASCOM drivers were very useful to connect the mount to the computer, and we found no problems in the installation, as we explained earlier.

We use the mobile phone's Onstep app to perform polar alignment. However, at this juncture we find some bugs. Sometimes it happens to set the alignment to four stars, then exit from the section "start align" (for example to focus the eyepiece), and returning to the section of the polar alignment we find that this is set on a single star. This is a problem because pressing "start align" again asks if the mount is "at home", so you have to start again.

As seen in the test section 6, the result are encouraging. The auto-guide seem to be stable and quite good since the RMS is lower than 1 for RA and DEC. Photography with this configuration have been set up with more than 2 minutes per pose (which was impossible for us before the devolving of this project). We think it is possible to increase the exposure time without problems.

As a final consideration, before buying an expensive telescope and mount, consider the idea of converting, if you have it, your old telescope, and then enjoy its developing!

Appendix

Stepper motors specifics

17HM15-0904S stepper motor

Electronics	
Manufacturer code	17HM15-0904S
Engine type	bipolar
Pitch angle (deg)	0.9
Torque (Ncm)	36
Rated current/phase (A)	0.9
Phase resistance (Ohm)	60
Voltage (V)	5.4
Inductance (mH)	12 ± 20% (1 kHz)
Physical specifications	
Frame dimensions (mm^2)	42x42
Body length (mm)	40
Shaft diameter (mm)	5
Stem length (mm)	22
D-cut length (mm)	15
Number of cables	4
Lead number (mm)	300
Weight (g)	280

Table 15: Nema 17 (0.9A) stepper motor specifics.

17HM19-2004S1 stepper motor

Electronics	
Manufacturer code	17HM19-2004S1
Engine type	bipolar
Pitch angle (deg)	0.9
Torque (Ncm)	46
Rated current (A)	2
Phase resistance (Ohm)	1.4
Voltage (V)	2.8
Inductance (mH)	4
Physical specifications	
Frame dimensions (mm^2)	42x42
Body length (mm)	48
Shaft diameter (mm)	5
Stem length (mm)	24
D-cut length (mm)	24
Number of cables	4
Lead number (mm)	500
Weight (g)	370

Table 16: Nema 17 (2A) stepper motor specifics.

11HS12-0674S stepper motor

Electronics	
Manufacturer code	11HS12-0674S
Engine type	bipolar
Pitch angle (deg)	1.8
Torque (Ncm)	7
Rated current (A)	0.67
Phase resistance (Ohm)	5.6
Voltage (V)	3.8
Inductance (mH)	4.2
Physical specifications	
Frame dimensions (mm^2)	28x28
Body length (mm)	31.5
Shaft diameter (mm)	5
Stem length (mm)	20
Number of cables	4
Lead number (mm)	300
Weight (g)	110

Table 17: Nema 11 stepper motor for the focuser motion specifics.