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AN UPGRADE OF THE HARPS-N SPECTROGRAPH AUTOGUIDER AT TNG

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Abstract

HARPS-N is a high-precision radial-velocity spectrograph installed on the INAF – TNG in the island of La Palma, Canary Islands. The HARPS-N project is a collaboration among several institutes lead by the Astronomical Observatory of the University of Geneva. The HARPS-N control software is composed by the Sequencer, which coordinates the scientific observations and by a series of modules implemented in LabVIEW for the control of the instrument front end, calibration unit and autoguider. The autoguider is the subsystem in charge of maintaining the target centered on the spectrograph fiber. It acquires target images at high frequency with a technical CCD and with the help of dedicated algorithms keeps the target centered on the fiber through a piezo tip-tilt stage. Exploiting the expertise acquired with the autoguiding system of the ESPRESSO spectrograph installed at the ESO Very Large Telescope (VLT), a collaboration has been setup between the HARPS-N Consortium and the INAF - Astronomical Observatory of Trieste (INAF – OATs) for the design and implementation of a new autoguider for HARPS-N. This paper describes the design, implementation and installation phases of the new autoguider system.

INTRODUCTION

HARPS-N (High Accuracy Radial velocity Planet Searcher - North) is an echelle spectrograph installed on the INAF – Telescopio Nazionale Galileo (INAF - TNG) in the island of La Palma, Canary Islands. It covers the wavelength range between 383 to 693 nm, with a spectral resolution R=115000. The instrument allows the measurement of radial velocities with the highest accuracy currently available in the north hemisphere and is designed to avoid spectral drift due to temperature and air pressure variations thanks to a very accurate control of pressure and temperature. HARPS-N is fiber-fed by the Nasmyth B Focus of the 3.6 INAF - TNG telescope through a Front End Unit (FEU). The two HARPS fibres (which inject the object and sky or a calibration lamp, respectively) have an aperture on the sky of 1"; this produces a resolving power of 115,000 in the spectrograph. Both fibres are equipped with an image scrambler to provide a uniform spectrograph pupil illumination, independent of pointing decentering.

The main scientific rationale of HARPS-N is the characterization and discovery of terrestrial planets by combining transits and Doppler measurements.

The HARPS-NpProject is a collaboration between the Astronomical Observatory of the Geneva University (lead), the Center for Astrophysics (CfA) in Cambridge, the Universities of St. Andrews and Edinburgh, the Queens University of Belfast, and the INAF – TNG Observatory [1].

HARPS-N Autoguider

HARPS-N current auto-guiding system (AG) has been developed in 2012 using the LabVIEW programming language. This choice has been driven by the requirements of controlling several devices in parallel:

- technical CCD (camera)
- piezo controller for the tip-tilt mirror
- 3-axis motion controller for the neutral density filters

The role of the autoguider is to correctly center the star on the fiber during the acquisition phase and to keep the star on the fiber, during the observation phase, by continuously moving the piezo tip-tilt mirror using small computed corrections in addition to the telescope tracking system. To do this, the software reads frames from the guiding camera at the highest possible frequency, computes the barycenter of the star and sends the corresponding corrections to the piezo tip-tilt mirror. The system also provides an integrated image algorithm for the calculation of the fiber hole center, improving the quality of the guiding system along the entire scientific exposure.

After few years of operations, the maintenance of the LabVIEW-based autoguider software proved to be difficult, due to strong dependencies both inside the LabVIEW VIs (Virtual Instruments) and between the AG and the Local Control Unit - LCU (Software which control the calibration unit of HARPS-N). The system startup was also very complicated due to several initialization phases, which slowed down the system considerably. For these reasons it was decided to re-design the entire software from scratch, trying to simplify it based on the experience gathered in several years of operations. Exploiting the expertise of the INAF – OATs, responsible of the design and the implementation of the autoguider system of the ESPRESSO spectrograph installed at the ESO VLT on Cerro Paranal in Chile [2], a collaboration has been setup between the HARPS-N Consortium and INAF – OATs for the design and implementation of a new autoguider for HARPS-N.

HARPS-N AUTOGUIDER DESIGN AND IMPLEMENTATION

The main goal of the HARPS-N autoguider is to maintain the target centered on the fiber hole during the whole scientific exposure. It has also the responsibility to provide the acquisition image to the Sequencer (the software in charge of coordinating the scientific exposure) during the acquisition phase to properly center the object on the fiber hole and to calculate the corrections for offloading the telescope in case of telescope drift/bad tracking.

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After the acquisition phase, the Sequencer sends commands to the autoguider for starting the acquisition loop of the technical CCD and starting the centroid and integrated algorithms which in turn allow to compute the adjustment needed to maintain the star continuously in position. Each minute the Sequencer checks also the AG system for the telescope offload corrections which are meant to offset the telescope such that the star is centered and piezo set in their nominal (middle) position. This is achieved computing corrections averaged over one minute with the aim to prevent that piezo drift too much outside the nominal position.

Hardware Architecture

The HARPS-N AG hardware is composed by the following parts:

- Shuttle PC, where the AG-Core module is installed. The OS is Linux Debian 9
- FLI (Finger Likes Instrumentation) ProLine 4210 camera
- Tip-tilt piezo controlled by a PI (Physik Instrumente) E-517 controller

Software Architecture

The new AG software consists of two modules (see Fig. 1): the AG-Core, implemented in C++11 and a web-based graphical user interface (GUI), based on Vue.js. They are described in the following sub-sections.

The two modules communicate using a REST implementation. REST (Representational State Transfer) is a software architectural style that defines a set of constraints to be used for creating web services. The GUI constantly polls the AG-Core through HTTP GET requests and is able to POST new parameters to the guiding loop. This design provides to be a very flexible way to interact with the AG-Core, even for eventual future remote observations, by having the AG-Core running at the telescope site and the AG GUI running on the observer machine.

AG-Core. The AG-Core software is implemented in C++11 and is composed by several threads (beside the main thread). The acquisition thread is responsible for the image acquisition and delivers each acquired frame to two synchronized queues (one for each algorithm). The centroid and the integrated image algorithm threads pop the frames from the respective queues and perform the computations to calculate the corrections for the piezo tip-tilt and the position of the fiber center respectively. The final correction is then send to the piezo software (also part of the AG-Core) responsible for controlling the piezo hardware. A further thread is responsible of getting the corrections for the telescope offload.

The communication with the FLI camera is realized through the FLI Software Development Library (version 1.40), which provides a core set of functions for programming FLI CCD cameras under Linux and Windows. The communication with the tip-tilt piezo is realized through the PI GCS2 library (version 2.4.0), which allows to control one or more PI controllers connected to a host PC.

A configuration file provides the configuration parameters needed in the AG initialization phase and at runtime. This file is written in JSON (JavaScript Object Notation) format and is read by the AG software using the Boost Property Tree library.

All the relevant information needed at runtime are stored in a Redis database. Redis is an open source (BSD licensed), in-memory data structure store which can be used as a database, cache and message broker.

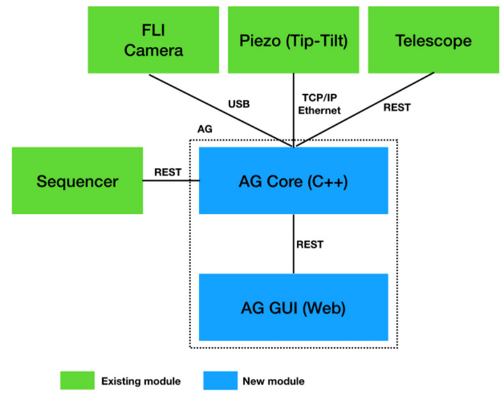

Figure 1: HARPS-N autoguider control architecture.

AG GUI . The AG GUI is composed by a panel composed by several tabs. The main tab (Field Stabilization) allows the user to visualize the live image, the image produced by the integrated image algorithms and the main algorithms status information; it also allows to set some parameters (e.g. technical CCD exposure time and algorithm radius mask). A second tab (Stabilization status) can be opened in case of algorithms warnings/errors, providing more detailed information about the algorithms status. Moreover, two engineering tabs are provided: the first one allows to set all the most relevant technical CCD parameters (exposure time, binning, etc.), to move manually the tip-tilt piezo and offset the telescope, the second one allows to change all the algorithms parameters.

The AG-GUI is based on Vue.js [3], a JavaScript framework for building user interfaces. This technology is used for creating standalone components that receive and send data through JavaScript events. In the AG GUI, components are represented by button groups, pixelated images and their settings, plots, buttons linked to the REST API, etc. The use of npm (node package manager) [4] allows to easily manage and add external open source JavaScript codes. Inside the AG GUI, the most used Vue.js packages are font-awesome, bootstrap-vue and vue-chartjs.

The npm build command is used to create a standalone minified HTML file with its dependencies. The AG GUI can be started by any host which locally has this HTML file: from an operational point of view the AG GUI is started by the Telescope Operator by opening this local file (optimized for Chrome) in the browser (see Fig. 2).

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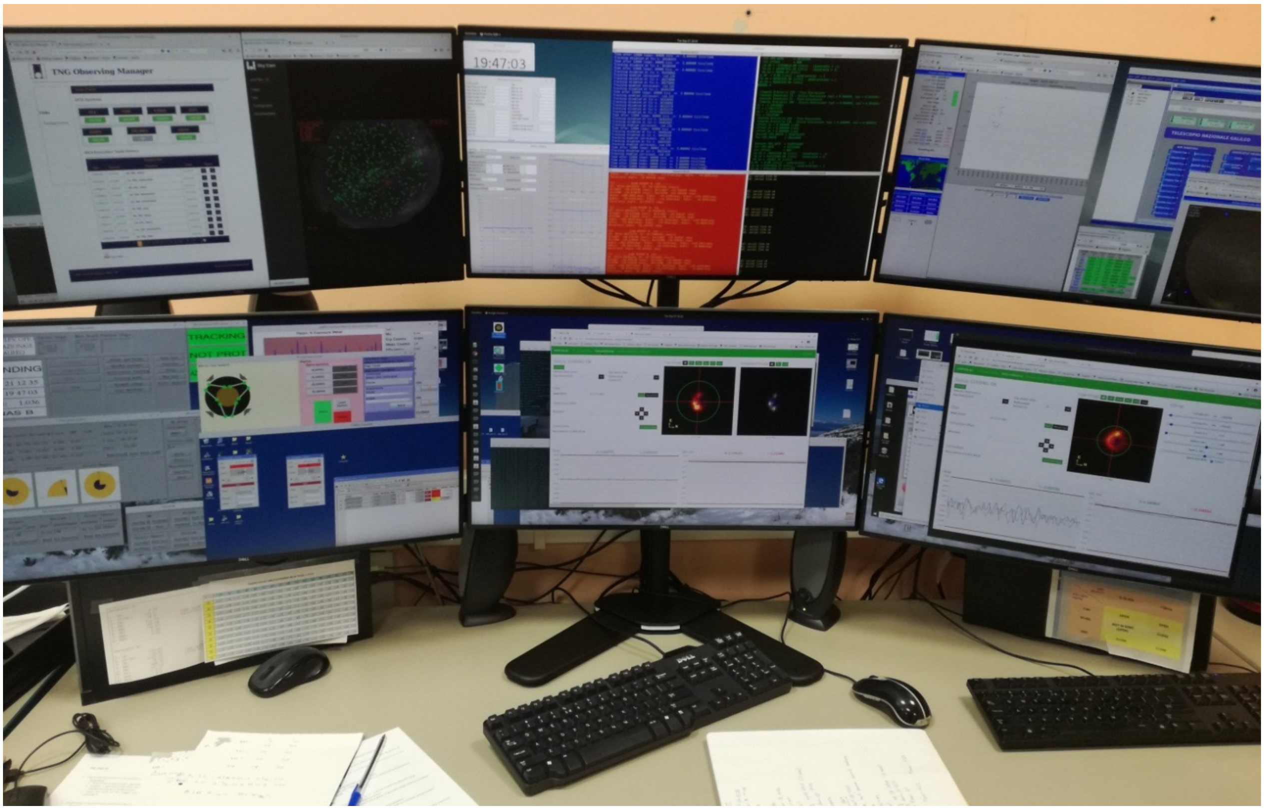

Figure 2: INAF – TNG telescope operator workplace. On the bottom right screens the HARPS-N AG GUI is visible.

AG Distribution and Installation

To minimize the build process requirements, ease the AG software installation and its future maintenance particular care has been taken to follow consolidated and well established DevOps practice. All the AG software, i.e. AG-core, but also AG GUI, is kept under configuration control using the GitLab web-based tool. Building, installing and packaging the AG software is achieved by using GNU Autoconf tools. These tools, via dedicated configuration scripts, generates automatically appropriate makefiles and ancillary files that are used afterwards to compile the source codes shielding specific characteristics of the target machine. Being the operating system of the target machine fixed, in principle, the usage of Autoconf tools would be not strictly necessary, however thinking to future maintenance and operating systems upgrades its usage will certainly represent, in the long term, an important benefit.

As described in the previous sections the new AG software relies on several open source libraries. Beside the adoption of Autoconf tools for the building phase, the usage of the "integration area" concept for the software installation was also foreseen. All the precompiled software libraries are kept under configuration control and installed via "tar" file in a dedicated directory, called integration root area. The Automake compilation process is instructed to link all the headers/libraries needed at compilation of the AG source code from this area (set via an environmental variable) and installs consequently the compiled executables in a dedicated directory. This has two benefits: the executable could be launched from "everywhere" in the system provided that the proper path is stored in the PATH environmental variable and that the whole software together with all the libraries can be installed within few minutes: just an "un-tar" is required for the libraries installation and a re-build, limited however, to only the AG source code. Keeping compiled libraries under configuration control has moreover the benefits to always ensure that the code correctly compiles (and runs) with exactly identified libraries versions thus preventing dependencies issues and speed-up re-installation in case of unexpected issues especially at night during ongoing observations.

AG Algorithms

Two algorithms are used by the autoguider to stabilize the image that enters the spectrograph fiber: the centroid and the integrated image. They are described in the following sub-sections.

Centroid The main task of this algorithm is to provide to the tip-tilt piezo the corrections to maintain the target centered on the fiber hole (1" diameter on sky). Each image acquired by the camera in the acquisition loop is analysed by this algorithm. This image is 60x60 pixels big with 1x1 binning and shows the fiber hole at the center surrounded by the (annular) target halo. The algorithm makes use of a user-defined circular radius mask centered on the fiber to perform background subtraction (taking into account what is outside the radius mask) and to calculate the image barycentre (using what is inside the radius mask). This radius can be adjusted by the user to properly isolate the target from the rest of the image (e.g. in case of close binary stars or crowded fields). The difference, in pixels, between the

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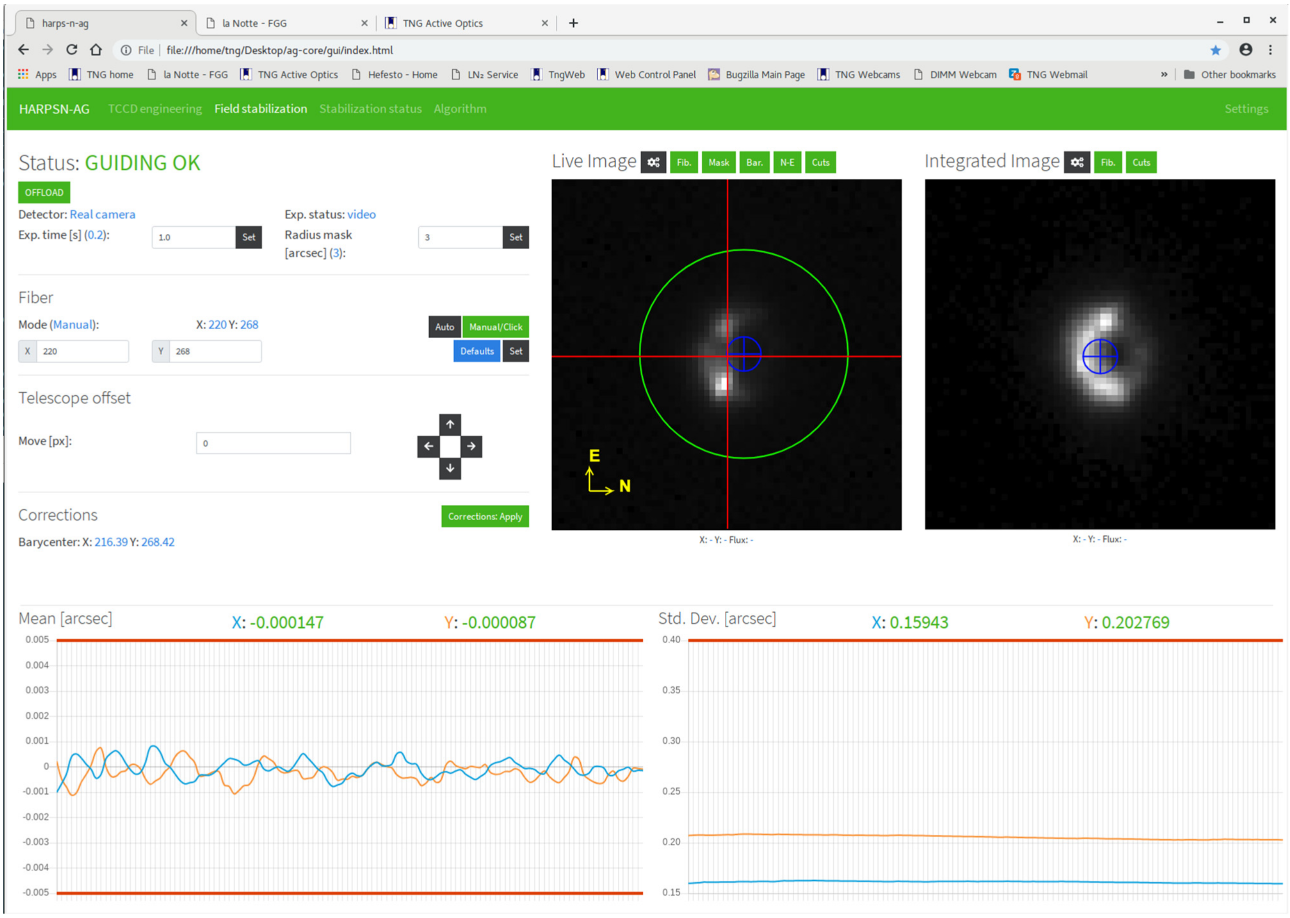

Figure 3: HARPS-N AG GUI (Field stabilization tab).

calculated barycentre and the fiber hole center represents the correction value to be sent to the piezo. In order to increase the algorithm robustness against seeing and flux variations, while maintaining a quite good overall accuracy in terms of stability, a Proportional – Integral – Derivative (PID) calculation is applied before sending the actual correction to the tip-tilt piezo. The autoguider software that control the piezo then applies to this correction a rotation that takes into account the angle between the technical CCD on sky and the piezo axes and converts the correction value to be sent from pixels to piezo physical units.

Integrated Image In order to mitigate the effects due to thermal drift and telescope vibrations of the position of the fiber center hole (being HARPS installed on the Nasmyth platform), a dedicated algorithm that computes the position of the fiber hole center has been implemented. In this algorithm, the acquired frames from the technical CCD are stacked together in order to obtain a “mean”, more stable, image with the target halo around the fiber hole. After a background subtraction, the algorithm divides this “mean” image in several “slices” around the fiber hole center in both X and Y dimension, in order to have two maximums of flux for each slice (at the two sides of the fiber hole). Then, for each slice, the two maximums are used to calculate the hole center along the slice. The median of these values (for X and Y dimensions separately) is used to calculate the position of the fiber hole center. This new value, written in the Redis database, is then used by the Centroid algorithm to calculate the difference between the calculated barycentre and the fiber hole center.

Algorithms Quality Checks In order to validate the correctness of the computed values, several quality checks are performed by the algorithms themselves. The centroid algorithm checks that the number of survived pixels after the background subtraction is above a defined threshold and that the computed corrections is less that a second threshold. The integrated image, beside the check on the survived pixels after the background subtractions, checks if the new computed fiber hole position is not too distant from the measured configuration value. Moreover, if the number of saturated pixels in the live image is above a fixed threshold, the fiber center coordinates are not updated in the Redis database.

As a general rule, if one or more quality checks fail, the corrections are not sent to the piezo or the coordinates of the fiber hole center are not updated.

FIRST COMMISSIONING RESULTS

In September 2019 the new AG system has been tested on the HARPS-N instrument at the INAF – TNG Observatory. In order to have the system working, the old AG computer running the LabVIEW code has been replaced by the new shuttle computer with the new AG installed. The FLI Camera has been connected to the new computer via USB

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and communication with the PI piezo controller has been changed from USB (used by the old AG system) to Ethernet.

Figure 3 shows the Field stabilization tab of AG GUI during one of the first observation with the AG properly working. To reach this step the first action was to properly determine all the required transformations between sky, CCD and piezo coordinates and subsequently to tune all the necessary AG parameters. As can be seen in Fig. 3 the system was able to deliver very good results on a Mv ~ 8 mag star already after the first trial: with an exposure time of 0.2 s (visible on top left) the mean correction (in arcsec units, visible on the two graphs, bottom) is less than 0.001 arcsec both in X and Y direction with an r.m.s. of the order of 0.2 arcsec, well within the scientific requirements. The left picture on Fig. 3 shows the live image together with the current centroid determination (red cross) and mask circle (used to compute the background, as described in sections above). Yellow arrows represent the sky N-E orientation and continually rotates based on the information received from telescope telemetry. The blue circle shows eventually the location of the fiber hole which is also reported, in X and Y CCD coordinates, in the "Fiber" section of the panel (middle part, left). The right image shows the result of the integrated algorithm computation and, as described, is used to continuously adjust/calculate the central fiber position.

As can be seen form the image, the available buttons on the GUI able to control the AG behaviour are really few; this was a precise requirement to minimize operations from the operator. She/he has only the possibility, beside the mask radius, to change the exposure time (which is precomputed based on a star magnitude) e.g. if observational conditions vary during the scientific exposure, pick (set) the central reference hole positions in case the integrated image is not working correctly and skip the corrections in case that centroid algorithm delivers too wrong values. Both last checks are anyway automatically performed by the algorithms themselves and corrections are anyway not set if computed values exceeds predetermined thresholds.

CONCLUSIONS

In this paper the design, implementation and installation of the new AG system for the HARPS-N instrument at INAF – TNG is presented, which represent a collaborative effort between the Astronomical Observatory of the University of Geneva and the INAF - OATs. A first commissioning of the new system took place in September 2019 and already the very first and preliminary results show the goodness of the chosen design, software development practice and installation in an already existing working environment. Future steps foresee a second commissioning, a sort of AG science verification, to install a new AG version with improvements based on the experience gathered in the first run and to better tune all the parameters in order to to reach the maximum possible performance. After the science verification the new AG will become the integral part of HARPS-N and will be delivered to the INAF - TNG Observatory for routine observations.

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