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Catch me if you can! The Rise of Smartcatcher

Jonas Rust, Pierre Garnier*, Antoine Le Gall**, Félix André**, François Bougeard**, Léonard Pineau***, Mariko Dunseath Terao**** and Sylvain Pernon******

** Univ Rennes, Master Calcul Scientifique et Modélisation*
Campus de Beaulieu, F-35000 Rennes, France
*** Univ Rennes, Master Mécanique Mécatronique*
Campus de Beaulieu, F-35000 Rennes, France
**** ArianeWorks*
CNES 2 Place Maurice Quentin, Paris 75001, France
***** Univ Rennes, Institute of Physics*
UMR 6251, F-35000 Rennes, France
****** Univ Rennes, Project Lab,*
F-35000 Rennes, France

Abstract

Students of the University of Rennes 1 are involved in the study and development of a 1:10 model of an innovative rocket stage retrieval system conceived by ArianeWorks. Modifications of the first prototype commissioned to *myCTO* were studied, designed and implemented to make it easily dismountable and transportable, using limited machined parts and off-the-shelf components for easy manufacturing and maintenance. Preliminary simulation programmes and detection codes were prototyped in Python. A functional real-time system was implemented in C, optimized and validated using a model rocket stage in well-controlled dynamical configurations.

1. Introduction

Space research and exploration are often perceived positively by the general public and many children are drawn towards science and technology by spectacular feats such as the close encounter with a comet or the detection of exoplanets and black holes. This initial interest however tends to fade with age, as technical challenges and accidents delay projects and their costs rise while to the taxpayers' view, more down-to-earth problems remain under-funded. In 2005, the CNES launched PERSEUS [1], a higher education program aimed at arousing students' interest in aerospace industry and technological innovations. The consortium includes national research centres, schools of engineering, vocational schools and universities as well as private companies. Research projects, supervised by PERSEUS coordinators and higher education teachers, can be part of an official curriculum or realized by students in their free time, as a complement to their academic education.

The agreement signed at the end of 2016 with the CNES allowed the University of Rennes 1 to hire Sylvain Pernon, the PERSEUS coordinator in charge of launcher systems. His missions consist in introducing students to space technology, suggesting projects and supervising their work while strongly encouraging them to develop their own solutions. His presence on the Science campus of Beaulieu boosted the development of the Project Lab, a collaborative space offering access to technical resources and CNC machines, many of which were purchased with the financial supports from CNES as well as Bretagne, Rennes communities and the University of Rennes 1. The creation of the Project Lab stems from the efforts to develop a new type of environment, between home and class rooms, where students can learn in a less formal, yet stimulating way. These so-called third places are particularly well suited for hands-on experiments which are very efficient in motivating less academically oriented students, but also those who are eager to discover the professional world before graduation. On-campus activities undertaken without the stress of formal examinations help build self-confidence in students as they are encouraged to propose their own solutions under the supervision of teachers who act more like coaches. Projects are carefully designed to suit a wide range of levels and backgrounds, allowing students to take risks, fail and persevere and thus acquire soft skills that are decisive in professional life but difficult to learn through traditional education. The hands-on approach of PERSEUS brings out

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the importance of academic knowledge when solving complex issues, much more convincingly than classes and textbooks. This is acutely perceived when the field of applications is demanding with high safety and reliability criteria as in the space industry.

Students participating to PERSEUS in Rennes have contributed to the supersonic rocket project SERA, the reusable rocket stage MiniApterros and since 2018 to the rocket stage retrieval system Smartcatcher. The latter is a 1:10 scale model of the structure developed by ArianeWorks. The first prototype was commissioned to *myCTO*, a very young start-up, now *Sparkmate*. The rapid emergence of new companies with unusual economical and organizational models reflect the need of agile development in the New Space industry.

The parameters of the study and the hardware and software for the Rennes Smartcatcher were chosen by ArianeWorks in order to keep the project easily accessible to students as far as costs, security and technical difficulties are concerned. Since the beginning, the students were however encouraged to imagine solutions that are scalable to the full size Smartcatcher. The project is challenging and motivating for the participants, who must collectively complete it within a few years. To provide technical documents and exchange information through regular meetings are thus an important part of their training and a good preparation to their professional life. When the students are frustrated by the lack of details given by those of the previous academic year, they experience first-hand the value of well-written reports!

Two students involved since the beginning in the development of the Rennes Smartcatcher, Antoine Le Gall and Félix André, were authorized by the teachers in charge of the Master's degree in Mechanical Engineering to substitute their investment for part of their practical work. The training was covered by a work contract of 200 hours over three months financed by ArianeWorks. Despite the Covid19 pandemic that broke out a few months after the start of the project, Antoine Le Gall and Félix André managed to fulfill their contract by taking home some of the manufacturing equipment. The code development was affected by the lack of opportunity for studying the protocol of signal detection, recording and transmission as well as the digital characteristics of raw data. Radar modules are small enough to be manipulated in student accommodation but echoes from nearby walls strongly perturb measurements compared to those obtained with the Smartcatcher reduced to 1:10 scale.

After graduation, Antoine Le Gall started his own business, Hippocampus R&D, based on skills acquired during his education and internships and dedicated to the production of functional prototypes for SME as well as large companies □[2]. While the creation of the company was still under discussion, he received the first Incub'Starter award of the Rennes Law Society to promote innovation in the legal professions and to encourage access to law [3]. As a student company supported by the University of Rennes 1 and Pépite Bretagne [5], it is hosted at the Project Lab since January 2022. The presence on the campus of the first start-up produced by PERSEUS Rennes is a great source of professional satisfaction for the teachers and inspiration for younger students. One of them, still in Master 1 and leading the development of MiniApterros in Rennes, is the deputy CTO of Hippocampus R&D.

This paper is organized as follows: after a brief introduction to the concept of Smartcatcher, we present the work in mechatronics for the improvement of the initial prototype delivered by *myCTO*. The next section describes the development of a system for the detection and retrieval of a model rocket stage. Tests performed to assess the validity of the work is discussed before drawing some conclusions and giving perspectives for the future.

2. Basic concept of Smartcatcher

The basic idea of the Smartcatcher is to dispense with the landing legs of the first stage of a Vertical Take-off Vertical Landing (VTVL) vehicle, replacing them by a ground or sea catching system. The advantages are:

- reducing the mass and hence improving launcher performance;
- transferring complexity from launcher to ground;
- giving more leverage to GNC to deal with the landing phase.

Important high-level performance parameters need to be considered, such as non-recurring and operating costs and impacts on CONOPS which must be minimized. Intrinsic reliability of the overall concept should be at least the same as for the system with the landing legs.

Several key functions are required: stage detection, determination of the landing position, establishing and maintaining physical contact, deceleration, assuring vertical stability, up righting the stage, transfer to another vertical or horizontal position on the ground. The main steps are illustrated in Figure 1.
The Smartcatcher system parameters must be robust over a range of values of several recoverable stage parameters such as position accuracy, vertical and horizontal velocity, rotational speed, stage pitch and yaw, landing weight, stage geometry and engine transition phase.

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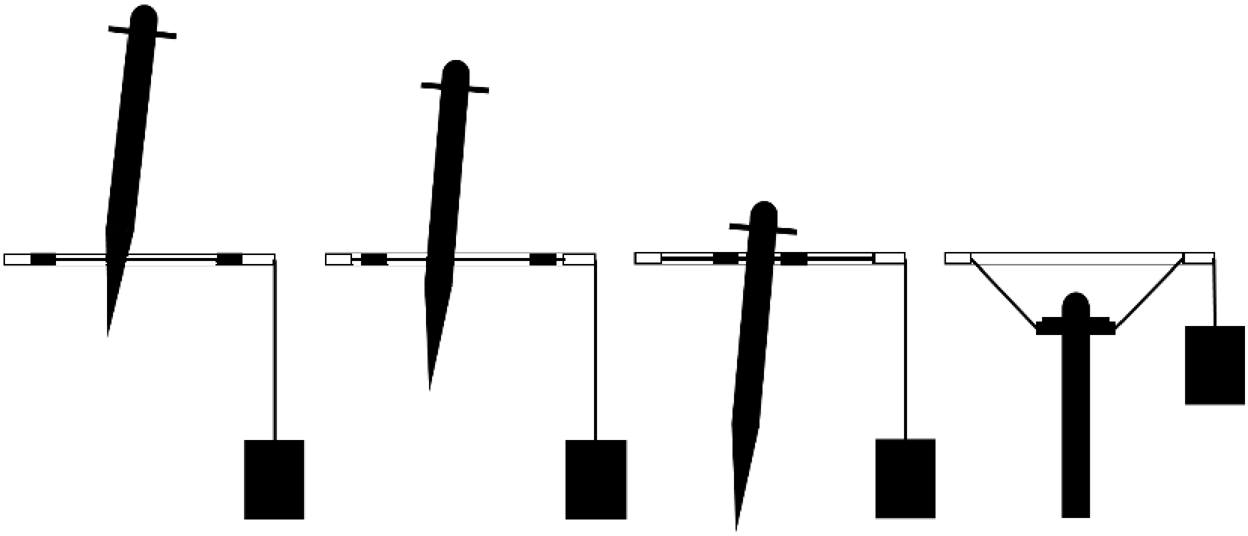

Figure 1: presentation of the main operating steps of the SmartCatcher concept

3. Mechatronic design and manufacturing work

The first prototype designed and built by SparkMate was mechanically welded, thus awkward to assemble and disassemble while not rigid enough to be propped up or extended. In order to make the structure conform to the specifications, a detailed study was undertaken by Antoine Le Gall and Félix André, who were at the time in the first year of the Master's degree in Mechanics at the University of Rennes 1. CAD was undertaken on the 3DExperience platform, a finite element modelling and simulation tool they used intensively during practical classes.

The first decision taken by the students was to rebuild the main structure with parts commonly used in theatre stage equipment. Four rails, made of 20 x 60 3-point profiles, are fixed on the frame to support mobile carts. Collars are fixed on triangular structures allowing various parts to be assembled, such as the mechatronic control and position tracking systems. The new structure has a mass of 123 kg, significantly less than the initial mass of 320 kg. The use of triangular sections instead of IPN was validated by static torsion simulations. A second level was also designed in order to match the specifications by extending the height of the structure to 4 m.

The retrieval system, composed of mobile carts on slide rails, was completely redesigned. The NEMA 34 motors chosen by *myCTO* were conserved as they matched the specifications. The performance and lifetime of the system were greatly improved and the possibility of accurately adjusting the rails to reduce slack was added. To further reduce costs, components used in CNC machines were introduced. Antoine and Félix opted for a solution based on two precision shafts housed in the profile grooves on which steel wheels with grooves roll. Each cart is carried by three wheels supported by axles whose dimensioning calculations were verified by testing. The whole unit is mounted on a profile, which allows the center distance to be adjusted, thus ensuring a perfect guidance of the slide. All the axles and other sensitive mechanical parts were designed to withstand the forces induced by the landing. The precision shafts were made from a single piece to guarantee a smooth guidance and have a chromium coating to avoid corrosion if the prototype is used outdoors.

The cable fixing and tensioning system were also substantially improved, in particular the cable return and the pins which turned out to have been initially undersized. The belt/pulley principle to set the trolleys in motion was conserved but the system was re-dimensioned to better withstand stresses. At the precise moment when the rocket stage is captured, its kinetic energy is dissipated by a spring/damper system installed on the engine blocks. A detailed study of the damping system was carried out, with assumptions of increasing complexity in order to satisfy the specifications set by ArianeWorks. Since damping coefficients are never mentioned in the technical documentation of shock-absorbers, experiments needed to be performed. The students used a Deltalab bench to measure the characteristics of Misumi C-MAKS2020M dampers recovered from previous tests for the SERA III rocket and to determine the equation of motion of their model system. Numerical simulations were also undertaken with Simulia and Dymola, two programs

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of the 3DExperience platform. Some simplifications had to be introduced to model the contact between the rocket stage and the cable but the mathematical results were confirmed by the simulation. The calculations and tests show that C-MAKS2020M shock absorbers meet the specifications of the Smartcatcher.

The students designed a plate through which the cables are attached, and translating freely with a two-bearing sliding linkage manufactured by IGUS, a regular supplier to PERSEUS. The plate is also in contact with the shock absorbers which are embedded in the carts. The cables are prestressed with two springs parallel to the dampers in order to reduce the sag while adding force to improve the damping. The complete system is raised with 20x60 profiles in order to take into account the volume occupied by the pulleys moving the carts.

The intersections of the cables carry the platforms which, upon detection of the rocket stage, must be quickly shifted to the landing point in order to securely catch it. To reduce friction, the cables pass through free pulleys mounted on bearings, with two perpendicular pulleys fixed under each platform. The pulleys were specifically manufactured by a technician at the University of Rennes 1 as no standard product was found to match the Smartcatcher specifications, while the platforms were printed in 3D.

The retrieval collar is made of aluminium and PEEK, a thermoplastic with excellent mechanical strength and high heat tolerance. The design was optimized to make it more reliable and robust, and a shock absorbing foam was added. After considering various materials such as cushioning gel, low elasticity rubber and natural rubber, low rebound urethane was added as it offers high impact and vibration resistance at a reduced price. An opening and closing system was also implemented to firmly catch the rocket stage before securely moving it to the final parking area.

A winch on a rail was installed above the main structure to lower a model rocket stage towards different points of the landing area. Figure 2 illustrates the global structure after improvement by the students of the Master’s degree in Mechanical Engineering. François Bougeard studied the retrieval collar, implemented the testing system and ran tests with Jonas Rust as explained in the fifth section of this article.

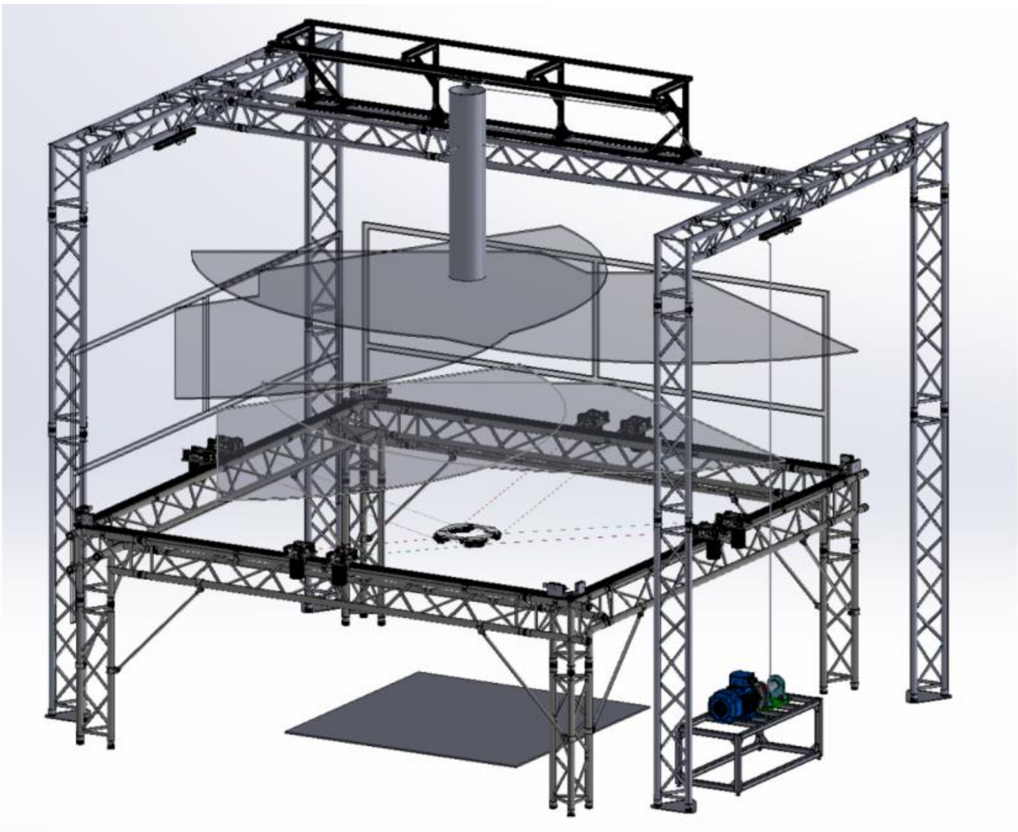

Figure 2: 1:10 Smartcatcher based on the first prototype commissioned to *myCTO*, improved and extended by the students of the Master’s degree in Mechanical Engineering.

DOI: 10.13009/EUCASS2022-7671

Antoine and Félix extensively redesigned the electronic architecture of the Smartcatcher coupled with the mechanical structure. The global system can be considered as a large numerical control machine with eight motors, each pair of which supports one of the four stretched cables on which the rocket stage will land. *myCTO* chose NEMA 34 stepper motors for their good torque/mass ratio, high resolution and low cost as they are often used in CNC machines. They are controlled by HBS86H closed-loop drivers which can calculate the number of steps actually taken using an integrated encoder. Control signals in G-Code are sent from an Open-source GRBL software code installed on two Arduino MEGA 2560 boards, each controlling a set of independent X- and Y- coordinates. A fixed stop was added to the carts to activate the end of travel sensor on the rail. To filter the signals from these switches, an interference suppressing circuit was included.

All the manufacturing steps were carried out in-house, which allowed the students to control delivery times. Parts were designed to be easily manufactured at the Project Lab where they had direct access to CharlyRobot CNC milling machines and several 3D printers including a BigRep. They also used additional tools available at the Center for Mechanics and Technology of the University of Rennes 1 where the Project Lab is housed: manual folders, conventional milling machines, drill presses, CNC turning machines and a waterjet cutting machine.

4. Software development

The aim here is to develop a suite of digital tools to detect a model rocket stage falling at a controlled speed, to accurately predict the landing position of its centre and to securely catch it with a collar composed of four parts carried by cables to absorb the landing shock. Each cable is stretched between two carts driven by stepper motors. Different scenarios must be considered, taking into account uncertainty in parameters and possible errors in measurements. Since the solutions must be applicable to the full-scale system, where distances are longer by a factor 10, the emphasis is put not only on the reliability and flexibility of the solutions proposed but also on the speed of execution of the computer codes.

A 2D sketch of the PERSEUS Smartcatcher is shown in Figure 3. The rocket stage with a typical diameter of 25 cm and the 3 m diameter landing site are not represented on the same scale. The cables carrying at each intersection one of the four capture collar segments are displaced by carts moving on fixed beams with respect to which the cables remain parallel. In Figure 3, the cables are arbitrarily positioned in a widely open configuration.

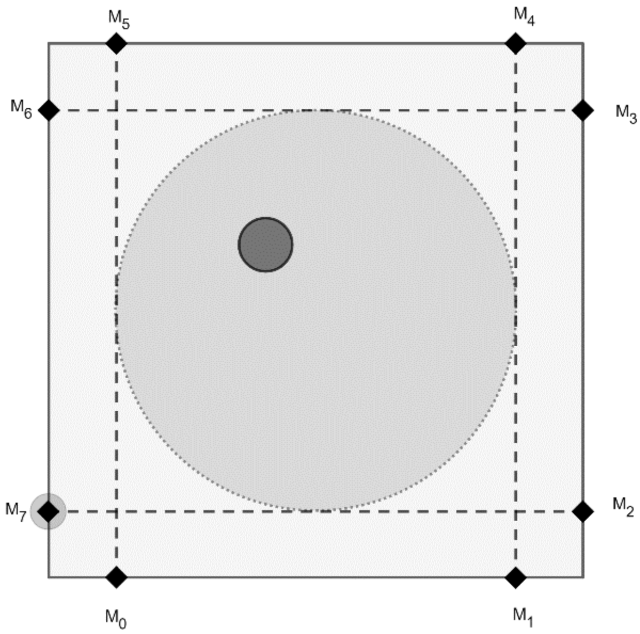

Figure 3: 2D representation of the Smartcatcher capture zone. The landing area is the light grey disk; the rocket is the dark grey disk; the mobile cables correspond to the dotted lines; each cable is controlled by 2 stepper motors, respectively M0 - M5, M1 - M4, M2 - M7 and M3 - M6

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A rough estimate based on the expected velocity of the 1 m long model rocket stage (maximum speed of 2.5 m/s, maximum tilting of 5 degrees) shows that the whole process of initial detection, tracking and displacement of the cables should take about one second. The cables should be positioned around the rocket stage with an accuracy of a few cm, in order to adequately distribute the mechanical stress on the capture collar.

4.1 Data retrieval

The detection of the rocket stage is performed using radar sensing, suitable for operations in an environment that is expected to be strongly polluted by flames and gases. For the PERSEUS Smartcatcher project, ArianeWorks chose the LT102 ultra-wideband radar module, produced by Aria Sensing [5]. It is a lightweight sensor suitable for indoor use, with a spatial resolution of 6.5 mm over a range of 10 m. It can be powered via a USB port and the power consumption is about 220 mW. It includes a microcontroller capable of processing digital data provided by the receiver, adapted to applications such as presence detection, position tracking and gesture recognition.

The first version of the code to retrieve data from the sensors was developed by Pierre Garnier in Python using SciPy, a library of high-level functions and classes to manipulate and visualize data which has recently become a firm favourite among students in science and engineering for quickly implementing and testing their ideas. Python codes are however generally too slow for real time operations, in particular since data cannot be accessed before the completion of previous write instructions.

The general principles tried and tested in the prototype code were then implemented in C, a general-purpose programming language commonly taught in higher education establishments, which offers several advantages over Python:

- used in operating systems and device drivers;
- fast executable machine code produced by compilation;
- low-level access to memory which gives the possibility of decoding binary data on the fly.

The C code runs on a Raspberry Pi that communicates with the sensors through USB 2.0 ports, using the same protocol for sending and receiving data packets. A state machine controls the reading step of the communication protocol so that data from all sensors can be read in parallel as soon as they are written, without having to wait for complete packets to be transferred from port to port. Scanning a 3 m wide area with a resolution of about 6.5 mm produces about 460 single-precision floats, or 1.8 kB. The code is able to read and handle about 50 packets per second and per sensor, a rate consistent with the 100 kB/s maximum write speed on a USB port. The bandwidth is independent of the number of sensors used (from 1 to 4 in our tests) and transfer errors are less frequent than with the Python code. The size of a packet increases with the scanning range and hence optimizing data transfer and processing speed will be essential for the full scale system.

4.2 Detection of the rocket stage

The LT102 sensor provides the amplitude of the echo detected by the radar as a function of the distance. Signals contain weak noise and spurious peaks of medium amplitude due to parts of the Smartcatcher standing in the sensor’s cone of sight. When a 1 m long, 25 cm diameter tube - mimicking the rocket stage - is placed directly in front of the sensor, a strong signal is recorded, whose location must be calculated as quickly and accurately as possible. To minimize delay, data transferred from the sensors are processed continuously and the following operations are performed:

1. square all amplitudes to reduce noise and spurious signal with respect to target signal
2. record the maximum of the empty amplitudes square which will be used as a cut-off threshold
3. when a strong peak appears, cut-off the signal
4. calculate the start, maximum and barycentre of the peak.

To test this approach, we placed the motionless tube at different distances to a sensor, respectively 1, 1.5 and 2 m. For each case, we calculated the mean distance over 500 data packets. The difference between the maximum and the barycentre varied between 4 mm and 38 mm, while the standard deviation appears to be most often smaller for the maximum than for the barycentre. This observation was empirically confirmed with several dozens of measurements performed later, as long as the target is correctly detected. Further experiments are envisaged to study in detail the influence of the rocket stage inclination and the detection height on the shape of the peaks and the accuracy of measurements. For the rest of the study, we used the maximum of the peak to evaluate the distance to the sensors.

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To determine the position of the rocket stage with respect to the Smartcatcher, it is necessary to detect the target in the plane of at least two sensors. Since the radar waves are reflected by the surface of the rocket, the centre of the rocket lies at the intersection of the two circles centered at the sensors and with radius equal to their distance plus the rocket radius. To minimize errors, we empirically defined the following protocol, using four sensors:

1. When a target is detected by at least two sensors, distances are calculated and if their dispersion is small, the motors are set in motion towards the first estimated landing point.
2. As time passes, new distances are measured and new retrieval positions calculated.
3. By crossing the data of four sensors, four positions are obtained and used to determine an average position within a sphere whose radius corresponds to the dispersion of the values and which depends on several factors such as the time step, the angle of the trajectory and measurement uncertainty.
4. The current center of the sphere is calculated by the sliding mean value over five successive measurements.
5. A new position is accepted only if it belongs to the sphere, since a position too far from the previous one has a large probability to be wrong.
6. The parameters of the sphere are continuously updated, to follow in real time the drift of the rocket stage position, for instance when its trajectory is inclined.
7. If no valid landing position is found after a fixed delay, the program starts to search for a new value in a completely autonomous way.

As standard deviations are small, we found that this protocol works very well with static targets. Certain areas are less covered by the sensors and results vary slightly with position. Targets placed far from the sensors and close to the structure of the Smartcatcher can emit signals that are weaker than the cut-off threshold.

Since the spurious signal due to the Smartcatcher structure is generally stable, a possible improvement consists in subtracting the empty signal recorded before the arrival of the rocket stage. This speeds up the processing of data from the sensors of the upper storey but would not apply to those from the lower storey since the motion of the motors controlling the wires modifies the background signal.

4.3 Recovery of the rocket stage

Each of the four cables used to capture the rocket stage is controlled by a pair of NEMA 34 stepper motors placed face to face on the lowest Smartcatcher beams. These motors provide a high torque, have a high resolution and a long lifetime and are furthermore light, quiet and inexpensive. They are often used in Computer Numerical Control machines such as CNC milling machines and 3D printers, which are required to efficiently perform accurate displacements in well-controlled environments. In the case of the Smartcatcher, the challenge is to develop an operational strategy to send instructions to a stepper motor, applicable in real time to a dynamical system whose exact behaviour cannot be fully planned in advance.

The Raspberry Pi which retrieves data from the sensors and calculates the position of the rocket stage sends instructions in G-code to two Arduino boards. Each of these sends digital pulses to the power driver of four stepper motors, one pair face-to-face on the X-axis and the second on the Y-axis, ensuring their synchronisation. The acceleration and deceleration ramps of the motors are also defined by the Arduino boards.

The ultimate objective of the Smartcatcher is to adjust the position of the cables to the position of the rocket stage in real time, as efficiently and reactively as possible. The main difficulty arises from the impossibility of cancelling an instruction sent by the Arduino to the stepper motors, whose execution delay is inherently difficult to predict accurately. It is therefore necessary to discretize the displacements and to send the instructions in a careful manner, in order to be able to modify them very quickly if a new landing position is calculated. To optimize the interception speed, it is obvious that the trajectory of the capture collar should be as smooth as possible, with few sharp stops and starts.

To control the stepper motor in real time, the only instruction available is G1, corresponding to linear displacements. By discretising the X- and Y-displacements into small steps, the global trajectory of the capture collar is curved. The overall speed is the speed of the motor that has the longest distance to run, while the acceleration is determined by the parameters stored in the Arduino. The speed and acceleration of the motor on the perpendicular axis are deduced to achieve the same acceleration time and runtime over the complete trajectory: the speed profile is trapezoidal, where the acceleration a is fixed and the acceleration time t_a is to be determined.

DOI: 10.13009/EUCASS2022-7671

Many tests have been performed to study the movements of the motors as a function of various parameters such as the maximum speed, maximum acceleration and displacements steps in the X and Y directions. We found that the first displacement, along the X-axis, should be long enough for the motor to reach the maximum allowed speed. The following steps *i* are performed by regularly increasing the displacement step along the Y-axis while decreasing that along the X-axis by an equal amount so that the sum remains constant. The step variation *h* is a parameter to be optimized empirically in order to obtain a trajectory for the capture crown as smooth as possible. In Figure 4, a comparison of velocity profiles in the X and Y directions is presented for two values of *h* and $\Delta x_i + \Delta y_i = 20$ mm so that $\Delta x_i = 20 - ih$ and $\Delta y_i = ih$ with *i* varying between 1 and 20/*h*. The maximum and average speeds are both larger in the case with the smallest value of *h*, leading to an overall smoother profile. We conclude that in this particular case, the value of $h = 0.5$ mm is a good compromise to achieve a fast interception while keeping the capability of modifying very quickly the capture collar trajectory if necessary.

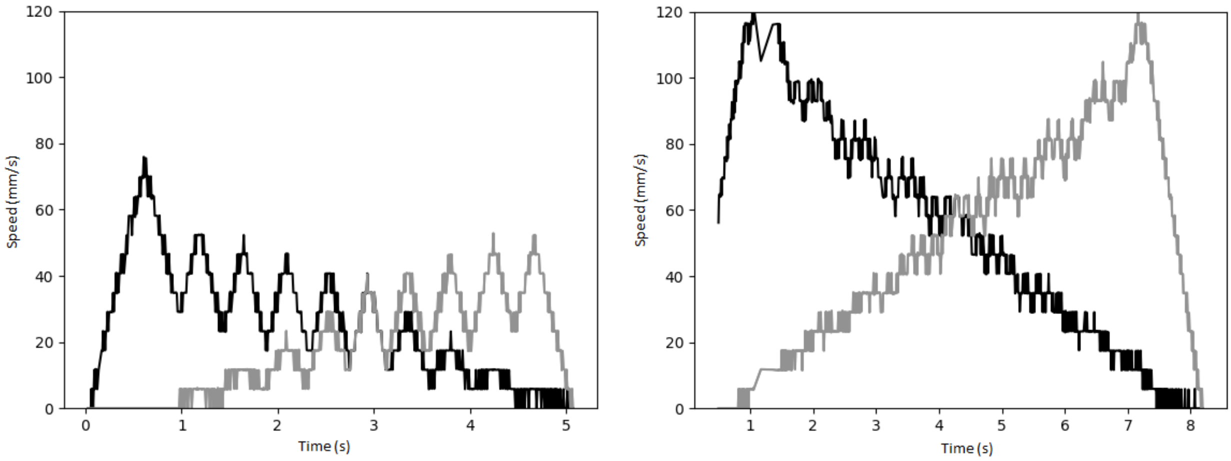

Figure 4: Velocity profiles of a NEMA 34 stepper motor driven in real time using the G-code instruction G1. Conditions on the displacements along the X- and Y-axes (resp. in black and grey): $\Delta x_i + \Delta y_i = 20$ mm with $\Delta x_i = 20 - ih$ and $\Delta y_i = ih$. Left: $h = 2$ mm, the maximum speed is less than 80 mm/s and there are about two marked deceleration and acceleration phases of about 50% along both axes every second. Right: $h = 0.5$ mm, the maximum speed of 120 mm/s is reached for both X- and Y-axes, the speed varies by less than 10% between acceleration and deceleration.

The retrieval operation is separated in two phases. The first one consists in following the position of the rocket stage in an almost closed configuration with a reasonable margin of error. During this phase, motors might be used on full power, especially when the landing position is not favourable. The second phase is triggered by a sensor located under the retrieval plane: the final position is determined precisely and the speed of the motors is decreased until the rocket stage is captured.

4.4 Experimental testing

Many trials have been undertaken, first to determine the best position of the sensors: if they are placed too high, the detection accuracy is degraded by the vibrations of the structure in the wind and approximations must furthermore be introduced to predict the trajectory of the rocket stage down to the capture plane. If they are placed too low, the signals are perturbed by interferences with the structure, especially when the landing site is not centered; time might be too short to place the capture collar in position, even more so if corrections of detection are necessary. We found that a height of 2 m with respect to the capture plane is a good compromise.

To simulate the capture of a descending rocket stage, a tube was lowered using a manual pulley. Tests were performed for different speeds albeit only at the centre of the Smartcatcher. They were conclusive in spite of some errors due to failure of a sensor or a poor detection threshold. Log files generated by the codes were used to identify the sources of problems in order to create test functions and introduce timeouts. After implementing these improvements, we found that the complete chain of detection and capture works well in a totally autonomous way

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5. Feasibility study

In our study, the diameter of the landing area as well as the height and diameter of the rocket stage were assumed to be fixed. The time available between detection and capture depends on the length and speed of the rocket stage and the height at which the sensors are placed. If the cables are initially tangent to the landing zone, the motors must have in the most unfavourable case enough time to run the distance equal to the diameter of the landing zone. Knowing the maximum acceleration and velocity of the motors, the minimum detection time and hence sensor height can be determined. Our study can be normalized by choosing the speed and acceleration of the motors, the speed of the rocket stage and the height of the sensors so that the detection - retrieval delay is identical to that of the real size Smartcatcher.

A 3D simulation software was developed on the GlowScript platform to visualize the behaviour of the system and to assess its limits for different parameters, such as the speed of fall, the position of the rocket stage and the speed of the motors. The first version of the code was written in Python by one group of students and made available to all other participants in PERSEUS. Animations in 3D were created using the VPython package. The simulation software was designed to work for the 1:10 model as well as the full-size Smartcatcher.

Another study was conducted in order to optimize the initial position of the cables within the landing zone and not tangent to it in order to reduce the acceleration and velocity of the motors. This initialization could be improved by adding a sensor at a greater height to determine an approximate landing position at an earlier time.

6. Conclusions and perspectives

In keeping with the philosophy of PERSEUS, the Smartcatcher project gives students the opportunity of applying theoretical concepts taught during their Master's degrees at the University of Rennes 1 and of acquiring new competences such as design optimization (use of standard off-the-shelf parts to reduce costs), electronics, electric motorization and validation by designing and implementing appropriate test suites.

The codes in C for the detection and in G-code for the recovery of the rocket stage are modular and well documented. The programs record intermediate data for *a posteriori* analyses such as calculated or verified positions, stepper motor speed profiles and raw signals. They can readily be exploited in user-friendly graphical interfaces whose development is planned in Python.

For further validation, the program can easily be adapted to other tests and data. This will be particularly useful for future experiments as the signals depend on the position of the landing site with respect to the Smartcatcher.

We have also started to consider a new approach to overcome the difficulty of knowing the precise moment a G-code instruction is executed, so that the real-time monitoring of the position of the stepper motors and hence of the capture collar becomes possible. The positions can be recovered on the Arduino using another G-code instruction and the development of the program for processing the data is ongoing.

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