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MASTER THESIS

Autonomous VTOL for avalanche buried searching
Avionics

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To my family and Laura

Abstract

The aim of the thesis is to inspect and derive a model for an autonomous VTOL that could help Mountain Rescue in finding the position of buried person under avalanche.

The first part of the thesis will inspect the state of the art in buried searching, ARTVA transmitter and searching algorithms. Also we will show some of the requirements and technical specifications for a searching drone.

In the second chapter we will expose the problem of searching the position of a transmitting source in near-field with ferromagnetic antennas. The chapter will be closed with a design for a digital ARTVA receiver

In the third chapter, a new kind of searching algorithm will be defined, including routines of obstacle-avoidance and altitude-keeping.

In the fourth chapter, a model of an hexa-copter and its stabilization controls are derived and simulated in MATLAB/Simulink. The loop is closed on some of the searching algorithm defined in the previous chapter. Results of searching routine are shown and critically examined.

The last chapter will take into account all the results to derive some conclusions about the stated problem, with some suggestions for further improvements.

There are so many person that helped me through this journey, that I should write an entire thesis only to name them all. But few of them actively suggested me the solution that you find in this text. First of all, Ermes Floriani, that started this project; the men and women of Italian Mountain Rescue Team, that risk their life every day to save person in danger, and helped us in finding information for develop a drone that could be really helpful; Ing. Paolo Bosetti and Ing. Francesco Biral that always believed and inspired me during the Master Course; Luigi Ghinassi, who gave me the intellectual instruments to understand and develop an ARTVA prototype; Matteo Cocetti, that has shared with me his genuine and innate mastering of mathematics and problem solving; my father that has always tried to find a solution for some of the usolveable problem that I've encountered.

There are many others, maybe not cited here, but firmly present in my heart. Thank you all.

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Introduction to Mountain Rescue

Contents

Many people in the last few year have re-discovered a passion for winter mountain sports. Some of them have decided to explore the extreme version of this sports, like winter climbing or free-riding.

The increasing number of riders in extreme snow condition facilitates avalanches falling. Mountain Rescue Team is often called for search probable buried hikers, constrained to operate in an environment with an high residual risk. To facilitate the research, national and regional laws[1] have imposed the use of ARTVA transmitter, also called *Avalanche Beacons*, for rider of non-equipped trails.

[1] Repubblica Italiana. Legge 24/12/2003 n. 363. *Gazzetta Ufficiale*, 2003

1.1 Some statistics about the avalanche accidents

During the year 2000, alpine countries decided to start an on line Database of avalanche victims, with the participation of the Italian council called *A.I.NE.VA.*. The statistics show a mean of 18 victims per year in Italy. The number of accident is clearly related to the higher number of avalanche phenomena, strongly associated to the rising number of riders that are using snowboard.

A.I.NE.VA: from the Italian *Associazione Interregionale NEve e VAlanghe*

A deeper analysis of the data shows that the 40% of the accidents have victims. Also, the number of buried was analyzed. Statistically:

- 60% of the accidents have only one buried
- 34% of the accidents have two or three buried
- 16% of the accidents have four or more or more buried

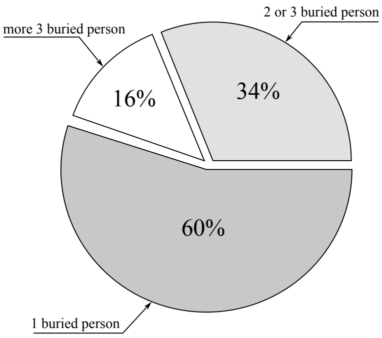

Figure 1.1: Number of buried

Another important factor is the position of the overwhelms hikers:

- 37% remain on the surface of the avalanche
- 28% are only partially buried
- 35% are completely buried

The survival curve, because of frostbite and hypothermia, without considerable traumas, has an upper limit of 15–18 minutes. Here is the the companion rescue that makes the real difference[2].

[2] Club Alpino Italiano. Manuale sci alpinismo. Technical report, Commissione Pubblicazioni CAI, 2004

One last important statistic is the number of hikers found with the ARTVA. Considering the fact that the statistics do not take into account the episode of auto-rescue, the 7% of the buried are found by the use of the receivers, a very small amount of the total. This data should be revised in the light of the advent of new digital ARTVA receivers, that simplify the searching method, and reduce the searching time [7].

ARTVA: from the Italian *Apparecchio Ricerca Travolti VAlanga*

As reported in [4], within Europe and North America, avalanche airbags and avalanche transceiver reduce mortality, and companion rescue reduces incredibly the median duration of burial, remarking the extreme importance of those device for all mountaineers.

1.2 Avalanche Beacons

There are two main typologies of avalanche transceiver. Differences are mostly in the user interface during receiving. We can divide in *analog* and *digital* ARTVA. Both device are equal for what concerns transmission. ARTVA can not be at the same time in transmission mode and receiving mode. Some models switch from receiving to transmission status after a scheduled amount of time.

1.2.1 Transmission Mode

During transmission, beacons transmit a so-called *wild-life tag*, or more simply, an intermittent signal at defined frequency, as stated in normative[3]. From the normative, it is possible to extract more informations about the transmitted signal:

[3] ETSI EN 300 718-(1 2 3 4). E.r.m. avalanche beacons - transmitter-receiver systems. Technical report, ETSI, 2001

- A1A Signal:
  - amplitude modulated signal

  - digital information (keying)
  - carrier frequency: 457kHz
  - no auxiliary carrier
  - frequency error shall not exceed ±80Hz
- carrier keying characteristics:
  - on-time: 70ms minimum
  - off-time: 400ms minimum
  - period: 1000ms ± 300ms
- H–field peak at 10m
  - must be greater than 0.5μA m^{-1}
  - must be lower than 2.23μA m^{-1}

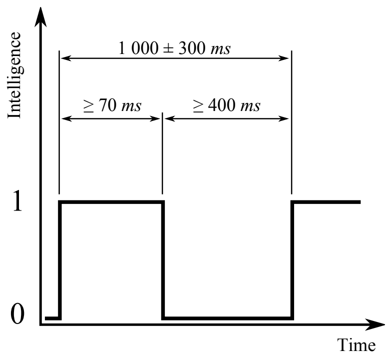

Figure 1.2: Intelligence signal of avalanche beacons

1.2.2 Receiving Mode

The normative states for receiver:

- the $(S + N)/N$ ratio of 6dB at the terminal of electro–acoustic transducer
- a clear optical indication of direction for beacon with optical signal indication of direction

The Italian authority in Mountain Rescue is *Soccorso Alpino e Speleologico Italiano*

Analog Beacons

The analog beacon uses a cascade of filters and an identification circuit to extract the strength information of received signal. The strength is thus used as gain command for a sound generator, that rescuer uses to identify the direction of arrival. Typically, those ARTVA have a volume knob to perform a fine search. The main drawback is the extreme difficulty to perform a fast search, that requires an experienced user. Quoting [6]: *a better term for analog beacon would be **audible–based***

Digital Beacons

Those beacons implements an user interface that indicates *the field line direction and an artificial distance to the center of the field*. This simplicity makes those beacons perfect for unexperienced user and autorescue: those device **are strongly advised by the Mountain Rescue for all hikers, experienced or not**.

Figure 1.3: Tracker DTS Avalanche Transceiver, a digital beacon

Must be noted that the algorithm inside those transceivers runs on a very low power DPS, due to energy harvesting requirements, so often the rescuer must slow down his speed to gave time to the beacon to analyze received data. Also, it was pointed out from manufacturers that advanced techniques, like multi-buried identification and buried status (hearth-beat) make use of frequencies different from the one described in normative.

1.2.3 Italian Mountain Rescue Intervention

What happens after an avalanche? We interviewed some of the professionals of the Mountain Rescue Team in province of Trento, and asked them to explain us the actual procedure.

Intervention on Avalanche

The intervention begin after a witness call. Usually the witness is one of the hikers that is on the accident location. In the best situation, the witness begins the companion rescue procedure, with his own avalanche beacon, and calls the emergency number.

During the emergency call, the operator tries to understand the location, alerts the rescue team on shift and tries to figure out the general situation that the team may encounter. A rescue unit is formed by:

- Mountain Rescue heli-ambulance expert
- Mountain Rescue canine unit
- Health equip and nurse

If heli-ambulance is cleared to take off, those are the first rescuers on the avalanche. The clearance is related to weather and light conditions, because flight is performed by eye-sight. If heli-ambulance mission is aborted, Mountain Rescue team have to reach the avalanche with ground vehicle.

Under certain strict condition, it is possible to perform an ARTVA search from the helicopter.

Once arrived on the location, if residual risk make it possible, the rescue team is dropped from the heli-ambulance and starts the searching procedure, with canine unit and with personal ARTVAs. The rescuers with the beacons follow a scheme that allow them to cover the avalanche front. This scheme is called primary search. While a signal is identified, the rescuer start a fine search to pinpoint the buried position.

Equipment

There is a procedural and moral obligation in having the last generation device, even if does not exist a directive that defines a specific model for the equipment. Each rescuer has a VHF transmitter and cellphone, along with the personal beacon.

It is possible to perform a search with other technology, like RECCO[4], even if the detector is heavy and not always reliable.

[4] RECCO is a passive searching method, composed by a reflector included in hikers clothing, and a detector used by rescue teams. A RECCO detector usually performs passive search and 457kHz avalanche beacons search at the same time. The last generation detector has an average weight of 1kg, while the reflector weights only few grams. RECCO cannot be used for companion rescue

1.3 State of the Art

In this section we will analyze the state of the art in the field of beacons construction and signal analysis.

1.3.1 Transmission

Normative states the use of a very long wavelength (λ) (656m). Such a long wavelength reduces the interference effects of snow, body and rocks and also multi-bouncing and multi-path effects[3] that may afflict some shorter waves. This is one of the main reason why GPS technology never erupted in this field[6].

This advantage also bring a consistent number of drawbacks, such as the fact that the search is always performed in near–field (distance less of $\lambda/2\pi$). In the near–field, as we will see, interpretation of flux lines is quite complex, and it is difficult to derive a general direction of arrival algorithm.

Avalanche transceiver for companion rescue has to be small, therefore antennas and batteries has to be small. As we will see in the next chapter, to increase receiver antenna gain (also called effective height h_{eff}), ferrite core antennas are commonly used, but the efficiency and the noise introduced is not good. Those brings to transmitter that may be identified in the range of 40 to 60m, in function of type of receiver.

There is no big evolution in transmitters; almost all devices implement a simple amplitude–shifting–key (ASK) transmitter, build with an oscillator for the carrier, and a variable gain amplifier that modulates the intelligence signal.

1.3.2 Reception

Usually, an analog receiver has a little more bigger receiving radius with respect to a digital one. This difference is due to stronger filtration routines implemented in digital ARTVA, with respect to analog, and because of the dimension of the z–axis antenna.

A digital ARTVA implements multiple antennas. Some typical configurations are:

- two crossing antennas
- three perpendicular antennas

The signal from whips are preprocessed using analog circuitry and then converted and processed in a DSP microprocessor. There are some advanced techniques[15] implemented for the identification of the direction of the vectorial H–field, and also to help hikers and rescuers to find a transmitter.

In general, the circuit may be resumed as follows:

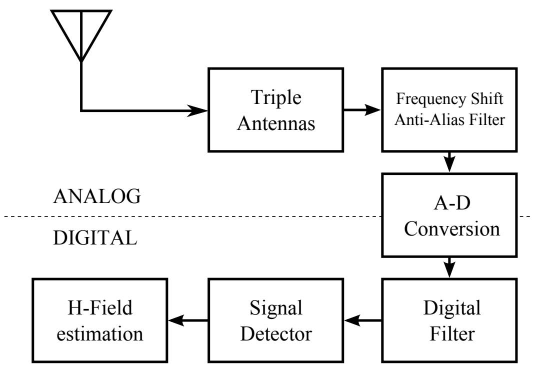

Figure 1.4: Block diagram of a commercial digital beacon, taken from [15]

- signal is received through the antennas
- the first stage of filtering is a frequency shift and an anti-aliasing filter, that is necessary to avoid problems during AD-conversion
- the signal is converted in the digital domain
- other filtration techniques are analyzed in [15], and are one of the main research topic in this field, in association with phase analysis to better understand the direction of the single components of the

H–field

- the signal detector and magnetic field estimator is implemented via software

One of the main challenge is the problem of the noise introduced by antennas. This noise is proportional to the received signal, phenomenon that induces an unsurmountable issue in the identification of multiple burial signal.

1.3.3 Searching Algorithms

The magnetic momentum problem

The main problem is the searching of the burial. Until now, only few are the example of automatic searching, while quite consolidated is the practice of the manual searching. One of the key aspects is the problem of the orientation of the transmitter: as we will see in the next chapter, the direction of the transmitter antenna change radically the shape of the field. From a general point of view, with respect to classical far–field identification problem, in this case we have to identify 6 state for each transmitter[5], instead of 3, while we can only collect 3 measurements (the H–field vector components).

[5] 3 states refer to the position of the transmitter, while the latter 3 refers to the magnetic dipole momentum that is parallel to the axis of the antenna

Even if there are some solutions for near–field qualitative direction of arrival, as explained in detail in [8], typically those algorithms require a very prohibitive electro–mechanical circuitry, not suitable as mountain equipment (or in our case, a drone).

So far, only one solution earns the right to be cited: the solution proposed in [13, 14], based upon Bayesian estimation theory and Kalman filters, is a remarkable attempt to find new approach to this problem, even if based on the weak assumption of a perfect knowledge of the covariance matrix related to the noise. One step ahead in this direction should be the redefinition of the problem in a dual form, from the Kalman filter to the information filter, in which the complete uncertainty is presented with a null matrix of the canonical form, instead of a infinite–valued matrix of the normal form.

Multiple Burial

Those algorithms do not analyze the problem of multiple burial, and the subsequent possible situation of overlapping signal. An almost complete dissertation about this problem, with some test on beacon present on the market, may be found in [11, 5]. From those technical documents, distributed by one of the most well-know company in snow–safety, rises the evident lack of a solution for the overlapping problem, due to transmitted signal limitation. The most suggest solution is to run–away from an identified source in the hope to find another new signal. Some producer try to avoid this using parallel carrier frequency with additional information coded into intelligence signal (unique ID, heartbeat status, ...). Those alternative frequencies are device/model dependent.

A complex procedure

Standard de facto is an algorithm of flux line following, in parallel with different assumption that user shall analyze, to derive the possible orientation of the buried person transmitting antenna, and subsequently find the best way to reach the hikers position. The complete explanation for the searching procedure is long even if not too complex, but based upon qualitative observation and deduction derived from expertise of the rescuer.

Generally speaking, what we need to know is the fact that a simple translation of this procedure in a machine with limited computational power is not practically possible.

A comprehensive description of the companion search and Mountain Rescue procedure could be found in [10].

1.4 *Autonomous VTOL for buried searching*

The thesis is built around the main thread of inspect and derive the avionics of an autonomous VTOL. Even if avionics refer to the complete set of instrumentation and algorithms necessary to stabilize and control the flight, in this work we will focus on some of the main aspects necessary to perform the main task of buried searching.

This work is not the first attempt to bring an automatic drone on avalanches. Some remarkable examples are

- SHERPA, European project born to create a robotic framework of helpers for Mountain Rescue, coordinated by University of Bologna
- An user–piloted quad-copter research is just started in Politecnico di Torino
- the project Alcedo from the Eidgenössische Technische Hochschule Zürich[6]

[6] Luc Oth Manuel Grauwiler. Fully autonomous search for avalanche victims using an mav, 2010

1.4.1 *Why the use of a VTOL?*

The use of a drone in the searching area depends on various factors. During design it is necessary to understand and think a system the fit entirely the actual search strategy.

One practical example of use could be a situation of high residual danger and an uncertainty about the presence of buried under the avalanche. In a case like that, the VTOL could be used to test the necessity of drop the rescue team on the avalanche.

The main advantage is obviously the ability to move faster on the avalanche with respect to an human rescuer, avoiding ground difficulties. At the same time, the drone should be able to identify and avoid obstacle like trees and ski–lift pillars.

1.4.2 *Quality Function Deployment*

The best way to define the characteristics of a new product is to inspect customer needs, and from qualitative user domain extrapolate quantitative engineering dimensions[7].

[7] Yoji Akao. Development history of quality function deployment. *The Customer Driven Approach to Quality Planning and Deployment*, 1994

Customer Needs

From our interviews of Mountain Rescue members, we have derived some conclusions:

- one of the main cause of an avalanche is the weather, that modifies snow characteristics; during one day multiple avalanches may fall, so it is fundamental to guarantee a long, even if discontinue, operative time
- the VTOL should be portable, with limited size and weight, but at the same time ready to be used in a short amount of time
- all design process should take in to account the extreme low temperature and the high altitude (lower air density)
- ARTVA device on the drone has to be robust with respect to electromagnetic interferences (propeller engines, radio, . . .)
- user interface is simple while complete
- the marking of the victims shall be hardware, with the use of visible darts

We are now able to define a table 1.1 in which at each customer needs a rating is given.

In future, the automatic recognition of the avalanche dimensions could be a good starting point for some advanced research in the field of computer vision, or the improvements of user interface using voice recognition over radio.

Customer Need	Rating
Identifies buried person	5
Is autonomous	5
Returns to rescuer position	5
Searches for the signall	5
Is fast	5
Marks physically buried position	5
Operates at avalanche temperatures	5
Performs more than one operation during the day	3
Is usable by anyone	3
Is robust with respect to EM interferences	5
Is portable in a 35L bag	3
Is quiet	2
Is compatible with other rescue vehicles	5
Disengages from the winch	5
Respects ENAC normatives	3

Table 1.1: Customer needs

Technical Specification

The next step in the definition of a good design is a list of technical specifications that will help us to identify the most challenging problems in and the gravity of those problems with respect to the costumer needs.

For sure, one of the first and most challenging complication is the weight reduction, that guarantees a longer flying time. Also those elements are related to the number of propulsion vector and the main dimension (the length of the arm). It is evident the correlation between the number of lift vectors with respect to the maximum wind interference.

For the definition of a good searching algorithm, as we will see, it is important a good resolution of position and attitude of the drone; while to avoid obstacle it is important the resolution and the maximum revealing distance of the range finders.

One final aspect that should be considered are the data related to the system that performs the marking of a buried person.

All the specifications are listed in table 1.2

Technical Spec.	Dim.
Flying time	min
Weight	kg
N. of antennas	
Battery Temperature	°C
Range Ultrasonic RF	m
Arm Length	m
Control TX distance	m
GPS Resolution	m
Lateral Speed	$\mathrm{m\,s^{-1}}$
Wind Speed	$\mathrm{m\,s^{-1}}$
ARTVA RX distance	m
Resolution Ultrasonic RF	m
Lift Force	N
N. dissembled pieces	
N. Darts	
N. Lift Vector	
Maximum inclination	rad
Operative height	m
IMU Resolution	$\mathrm{m\,s^{-1}}$
Weight Marking Device	kg
Weight Dart	kg
Weight ARTVA	kg

Table 1.2: Technical specifications

Merging the tables and comparison

In table 1.3 all data are compared with a weighting method. The table shows the comparison between technical specifications and customer needs and also between technical specifications and the other technical specifications.

How to read table 1.3:
Cust. needs vs. Tech. spec.:
○ no relation
◑ light relation
● strong relation
Tech. spec. vs. Tech. spec.:
▼ negative strong relation
▽ negative light relation
○ no relation
△ positive light relation
▲ positive strong relation

Components selection

From the merged data it was possible to select the components that

	Flying time	Weight	N. ARTVA antennas	Battery Temperature	Range Ultrasonic RF	Arm Length	Control TX distance	GPS resolution	Lateral speed	Wind speed	ARTVA RX distance	Resolution Ultrasonic RF	Lift Force	N. dissembled pieces	N. Darts	N. Lift vector	Maximum inclination	Operative Height	IMU resolution	Weight Marking Device	Weight Darts	Weight ARTVA
Identifies buried person	●	○	●	○	○	○	○	●	◑	○	●	○	○	○	●	○	○	○	○	◑	◑	◑
Is autonomous	◑	●	●	○	●	○	●	●	◑	●	●	◑	○	○	○	○	○	○	●	○	○	○
Returns to rescuers position	●	○	○	○	○	○	●	●	◑	●	○	●	○	○	○	○	○	◑	◑	○	○	○
Searches for the signal	●	○	●	○	○	○	○	●	●	○	●	○	○	○	○	○	○	●	◑	○	○	●
Is fast	◑	●	○	○	◑	●	○	●	○	●	○	●	●	○	○	●	●	○	●	◑	○	○
Marks physically buried position	○	○	○	○	○	○	●	●	○	●	○	●	○	○	●	○	○	○	●	◑	●	○
Operates at avalanche temperature	○	○	○	●	○	○	●	●	○	●	○	●	○	○	○	○	○	●	●	●	○	○
Performs more than one operation during the day	●	◑	○	●	○	○	○	○	○	○	○	○	◑	○	◑	◑	○	◑	○	○	◑	○
Is usable by anyone	○	○	○	○	◑	○	◑	○	○	○	○	○	○	●	○	○	○	○	○	◑	○	○
Is robust with respect to EM	○	○	●	○	○	○	●	●	○	●	◑	○	○	○	○	●	○	○	●	○	○	●
Is portable in a 35L bag	○	●	○	◑	○	●	○	○	○	○	○	○	○	●	●	●	○	○	○	○	◑	●
Is quiet	○	○	○	○	○	○	○	○	◑	○	○	○	◑	○	○	●	◑	○	○	●	○	○
Is compatible with other rescue vehicles	○	○	●	●	○	○	○	●	○	○	●	○	○	○	○	○	○	○	○	○	○	○
Disengages from the winch	○	◑	○	◑	○	◑	○	○	○	○	○	○	○	○	○	○	○	○	○	○	●	●
Respects ENAC normatives	○	●	◑	●	●	●	●	◑	◑	◑	○	●	○	○	○	●	○	●	○	◑	◑	◑

	Flying time	Weight	N. ARTVA antennas	Battery Temperature	Range Ultrasonic RF	Arm Length	Control TX distance	GPS resolution	Lateral speed	Wind speed	ARTVA RX distance	Resolution Ultrasonic RF	Lift Force	N. dissembled pieces	N. Darts	N. Lift vector	Maximum inclination	Operative Height	IMU resolution	Weight Marking Device	Weight Darts	Weight ARTVA
Flying Time		▼	▽	▽	○	▼	△	△	▽	▽	○	○	▽	▽	▽	○	○	▽	○	▼	▼	▼
Weight			▲	△	○	△	○	○	○	△	○	○	△	▲	▲	▲	○	○	○	▲	▲	▲
N. ARTVA antennas				○	○	○	○	○	○	○	▲	○	▽	▲	○	○	○	○	○	○	○	▲
Battery temperature					○	○	○	○	▽	○	○	○	▼	○	○	○	○	▲	○	○	○	○
Range Ultrasonic RF						○	○	○	△	△	○	▼	○	○	○	○	▲	○	○	○	○	○
Arm length							○	○	▲	▲	○	○	▽	○	○	○	△	○	○	○	○	○
Control TX distance								△	△	○	○	○	○	○	○	○	○	○	○	○	○	○
GPS Resolution									○	△	○	○	○	○	○	○	○	○	▽	○	○	○
Lateral speed										○	○	○	▲	○	○	▲	▲	○	○	○	○	○
Wind speed											○	○	▲	○	○	▲	△	○	▲	△	△	△
ARTVA RX distance												○	○	○	○	○	○	○	○	○	○	▲
Resolution Ultrasonic RF													○	○	○	○	○	○	○	○	○	○
Lift Force														○	○	▲	△	▲	○	○	○	○
N. disassembled pieces															▲	▲	○	○	○	△	△	△
N. Darts																○	○	○	○	▲	▼	○
N. Lift vector																	▲	▲	○	○	○	○
Maximum inclination																		▽	○	○	○	○
Operative Height																			○	○	○	○
IMU Resolution																				○	○	○
Weight Marking Device																					▲	○
Weight Darts																						○

Table 1.3: Comparison Table

will be used in the prototype. All components are listed in table 1.4

Table 1.4: Components list

N	Component	Description	Price
1×	Autoquad 6 Flight Controller	Imu board and stabilization controller	299.00€
6×	Autoquad ESC32	Electronic speed controller	239.40€
6×	Flyfuino HE4108 700kV Outrunner	Motors	299.40€
6×	HQ 12″per 4.5″CW and CCW Carbon propeller	Propeller	73.80€
2×	SLS Xtron 5000mA h 14.8V	Batteries	119.98€
3×	USB UART Adapter	Bridge between USB and device UART	9.90€
		Total	1041.48€

We have also decide not to use a commercial ARTVA, but instead try to build a digital one from scratch. This will allow us to get a lighter model, and also extract exactly the information that we want from the received signal. Even if some device have a serial port, the output data are filtered with models that incorporate the possible speed of a rescue, that is different from our VTOL.

List of Symbols (draft)

Symbol	**Description**
c	`\symc` — Speed of light (no)
λ	`\symlunghezzaonda` — Electromagnetic Wavelength (yes)
h_{eff}	`\symaltezzaeffettiva` — Effective height of loop antenna (yes)

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