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***Abstract*—Harmonic entomological radars have been used in the last decades to track small and lightweight passive tags carried by various insects, usually flying at low altitude and over flat terrain. Despite being exploited in many applications, not a lot of progress was achieved in terms of performances over the years. This paper reviews the research work done in this topic throughout the European LIFE project STOPVESPA, from 2015 to 2019. The main objective of LIFE STOPVESPA was to contain the invasive Asian hornet *(Vespa velutina)* and prevent it from further invading Italy. Among the foreseen activities, a new harmonic radar has been developed as an effective tool to locate the hornets nests to be destroyed. A preliminary prototype, based on a magnetron generator, was tested in 2015, showing a detection range of about 125 m. A first upgrade of this prototype was released in 2016, allowing to increase the detection range up to 150 m. A new approach, based on a solid state power amplifier and a digitally modulated signal, was then adopted for the second prototype developed in 2017 and extensively run in 2018; the detection range raised to 500 m. A last engineered prototype was eventually built for the 2019 summer campaign with additional improvements. This tool has been extensively validated over the last years with the Asian hornet but it has potential for tracking and monitoring many other flying insects.**

I. Introduction

A. Harmonic radars for entomological applications

Harmonic radars can be used to track insects flying at low altitudes and over flat terrain. Their operating principle is to use a passive lightweight transponder to double the fundamental frequency of the signal transmitted from the radar and use it as the receiving signal. Transponders can be detected and located without interference from environmental reflection (clutter) because these unwanted signals are included in the fundamental frequency and can be filtered out. Measuring the time delays between the transmitted and received signals allows to determine the distances of the transponders from the radar; the direction of arrival comes from the position of the mechanically rotating antennas in the horizontal plane.

Handheld systems based on a RECCO transceiver (for instance the ones described in [1], [2], [3] and [4]) are usually included in the harmonic radar category even though they are not able to determine the target range but only measure the received signal strength. All entomological radars reported in literature, no matter their specific applications, were found to be either limited in distance (all RECCO based devices reported above, [5] and [6] to mention a few more) or to flat terrain ([7], [8], [9]). We refer the interested reader to [10], [11] and [12] (and included references) for an overview of the most recent applications of radars concerning entomological studies.

To summarize, from the pioneering work of [8], no resources were devoted in trying to improve the harmonic radar capabilities, for instance extending its application to more hilly environments. This was exactly the need that drove our research in the last five years.

B. The case of Vespa velutina

The yellow-legged hornet (*Vespa velutina*) is a social insect native to tropical and subtropical areas of South East Asia [13], spreading in Europe since 2004 [14], [15], [16], [17]. This hornet has been included in the European invasive alien species list because of the large damage it can cause to other pollinating insects [18], [19]. EU Member States are therefore obliged to adopt surveillance action plans and control strategies against this species; the LIFE STOPVESPA European project started in 2015 as the Italian proposal to contain *V. velutina* and prevent it from further invading Italy.

Early detection of nests is one of the best available strategies to control the proliferation of *V. velutina* [18]; however, detection based on visual observation is quite difficult and time consuming [20] since the nests of the yellow-legged hornet are mostly built in hidden places, especially on tree tops and covered by leaves. A further difficulty can be the environment itself, which may be characterized by hills and woods, as in our area of interested, i.e. the Liguria region in Northern Italy. Moreover, colonies are often spotted late in the year when the reproductive phase is already concluded [21]. For these reasons, a way to discover colonies before they reach the reproductive phase would be of great importance for pest control. This need motivated the development of our harmonic radar, which can locate nests so they can quickly be destroyed; such a prompt response could eventually halt the spread of hornets as mandated by EU regulations on invasive alien species. This paper documents the evolution of our radar prototype throughout the LIFE project.

Our entomological tracking radar could also be applied to study several other insects (honeybees, caterpillar moths, beetles, carabids, butterflies, stinkbugs, etc.) for the broader range of applications mentioned in [12].

II. System architecture

While referring the interested reader to our previous work ([22], [23], [24], [12]) to detail the improvements over time, we would first like to shortly outline the overall architecture of our prototype.

Radar systems are generally constituted by a transmitting (TX) module and a receiving (RX) one operating coherently. In our prototype the transmitting and receiving signals were at 9.41 GHz and 18.82 GHz respectively. These values are a trade-off between the transponder size (as small as possible to be carried by an insect), the antenna horizontal dimension (as large as possible to increase gain) and free space path loss (the lower the frequency, the better). A Field Programmable Gate Array (FPGA) took care of the analysis of the received signal. The missing link between TX and RX systems was the passive lightweight transponder (also herein referred as tag), which doubled the fundamental frequency of the transmitted signal from the radar and re-transmitted it back to the receiver. As mentioned above, the measure of the time delays between the transmitted and received signals allowed determining the distances of the transponders, while the direction of arrival corresponded to the pointing direction of the mechanically rotating high directivity antennas in the horizontal plane. The radar hardware was hosted in a case installed on top of a telescopic tower (available from the second year on), together with the mechanically rotating antennas. All the system was powered by a commercial portable power generator (available from the second year on) and a standard laptop was required to immediately visualize the radar output. Figure 1 shows the usual radar setup (in particular the 2019 last prototype) in operative conditions. The total weight of the radar system was approximately 50 kg for all prototypes.

To guide the reader among the developed prototypes over time, here is a quick review of them all. A preliminary prototype (labeled P1a, see [22]) was tested in 2015, showing a detection range of about 125 m. A first upgrade (P1b, see [23]) was released in 2016, allowing to increase the detection range up to 150 m. Figure 2 reports the block diagram of the first two radar prototypes (P1a,P1b). A new approach was then adopted for the second prototype (P2a, see [24], [12]) developed in 2017 and extensively run in 2018; the detection range raised to 500 m. A last engineered radar (P2b) was eventually built for the 2019 summer campaign with additional improvements. Figure 3 shows the block diagram of the last two radar prototypes (P2a,P2b).

Fig. 1. Standard radar setup (P2b). The TX and RX antennas can be spotted on top of the system, covered by a radome. Most of the radar hardware was stored in the rack hanging right below the rotary joint. A telescopic tower helped to operate the radar up to about 6 m from the soil in order to avoid obstacles, such trees or bushes.

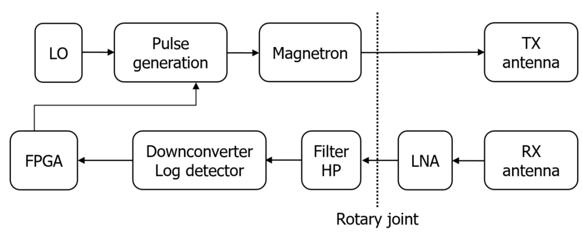

Fig. 2. Harmonic radar block diagram (P1a and P1b). The rotary joint dashed vertical line divides the rack case containing most of the electronics from the rotating head of the radar, which is made up of the TX and RX antennas and the LNA.

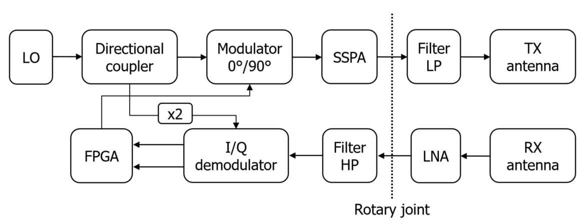

Fig. 3. Harmonic radar block diagram (P2a and P2b). The rotary joint dashed vertical line divides the rack case containing most of the electronics from the rotating head of the radar, which is made up of the LP filter, the TX and RX antennas and the LNA.

A. The TX module

The transmission module is the part of the radar that has been more considerably improved over time. At the beginning, mainly to keep the cost of the system at a reasonable level, P1a was equipped with a TX module derived from a commercial off-the-shelf marine radar built by FURUNO, namely the DRS25A model[1]. It was essentially a 25 kW magnetron

[1]www.furuno.com

generator transmitting pulses at a fixed frequency of 9.41 GHz, equipped with a horizontally polarized mechanically rotating slotted waveguide antenna 180 cm long. The generator was configured to operate with the minimum pulse width (100 ns) to maximize the range resolution and with the higher pulse repetition frequency (3 kHz) to improve detectability; the rotations per minute were 48.

In P1b we added a commercial WR90 waveguide filter, right before the TX antenna, in order to reduce the unwanted emissions at 18.82 GHz. Even though the TX antenna is supposed to emit only at 9.41 GHz, there was a small emission at the second harmonic, hence disturbing the received signal. The main upgrade of the TX system consisted in the adoption of a new TX antenna with vertical polarization instead of the previous horizontal one (see Figure 6). This change was driven by the fact that a vertical tag (as the one in [9]) is almost always co-polarized with respect to the tag during the flight of the insect, no matter its orientation. The new antenna, a 150 cm long slotted waveguide with 50 radiating elements (slots), was designed with the help of the commercial code CST-MWS[2] and entirely manufactured by the Antenna and Electromagnetic Compatibility Laboratory (LACE) of the Department of Electronics and Telecommunications of Politecnico di Torino. The radiation diagram roughly corresponded to the one produced by the FURUNO antenna, with a maximum gain of about 26.5 dBi. An intermediate solution was also tested, i.e. the adoption of launchers with circular polarization, to get rid of any inconvenience due to the tag orientation. However, we measured a decrease of the antenna gain and a consequent remarkable reduction of the detection range. This solution was discarded after testing.

In both P2a and P2b we directly designed and assembled the TX module. It included a 9.4 GHz dielectric resonator local oscillator, a directional coupler (to split the power between the TX modulator and the RX de-modulator), a modulator (responsible of the digital BPSK modulation), a solid state power amplifier (SSPA) and a set of low-pass filters to drastically reduce the TX leakage at 18.8 GHz. The same FPGA in charge of processing the received signals was used to command the TX module. In P2a a vertically polarized slotted waveguide (50 radiating elements, same as in P1b) was mounted, while in P2b a more directive slotted waveguide antenna (70 radiating elements) was adopted. The main focus of the P2b prototype was also related to the system assembly, which was more compact, as Figure 4 shows.

Table I summarizes the main TX parameters for all prototypes.

B. The transponder (tag)

The adopted transponder was made up of two copper pieces connected to a zero bias Schottky diode that generated harmonics of the received signal, i.e. from an incoming signal at 9.41 GHz to the strongest generated signal at 18.82 GHz.

[2]www.cst.com

TABLE I
COMPARISON OF THE PERFORMANCES OF THE DIFFERENT PROTOTYPES

Radar prototype	**P1a**	**P1b**	**P2a**	**P2b**
Peak output power [kW]	25	25	1	1
Pulse width	100 ns	100 ns	45 μs	45 μs
Pulse repetition frequency [kHz]	3	3	1	1
Revolutions per minute	48	48	20	20
ADC dynamic range [dB]	96	84	84	84
TX/RX Antenna polarization	H	V	V	V
TX antenna gain [dBi]	28.5	26.5	26.5	29.9
RX antenna gain [dBi]	27.4	27.3	27.3	30.6
Modulation	OOK	OOK	BPSK	BPSK
Processing gain [dB]	0	0	30	30

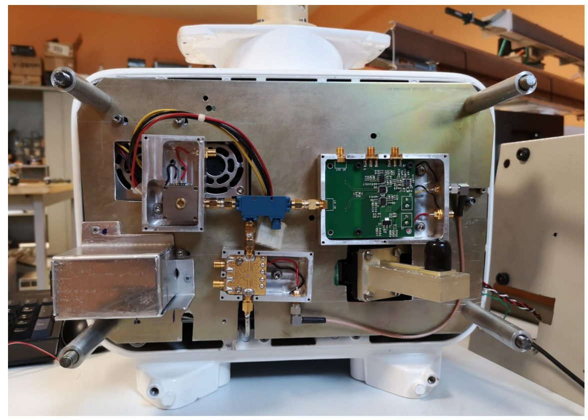

Fig. 4. All hardware was singularly packed and housed within a metallic box connected to the radar case.

Starting from the work described in [25], we investigated several tag geometries. In P1a, due to the horizontal polarization of the TX signal, we opted for a "loop" tag glued along the hornet thorax, weighting approximately 12 mg (see Figure 5A). The best configuration was found with a 0.25 mm diameter wire and with a total length of 16 mm, with symmetrical branches on both sides of the diode. This solution was not perfect, because when the hornet was flying to or from the radar, there was no signal at all impinging on the transponder (it was cross-polarized to the incoming wave) and, therefore, no re-transmitted signal to the base station. This limitation could be bypassed with a "X" tag made of two orthogonal loop tags secured to the insect with a cotton strand (Figure 5B). The increased weight was a substantial problem, above all in spring when the hornets were not strong enough to carry it; in addition, it was often ripped up by the insect or stuck in the tree branches. A "W" configuration was also studied (Figure 5C) in order to get rid of the same problem with less drawbacks. It was however very difficult to manufacture two tags with the same omnidirectional pattern and, when we moved to printed solutions, we noticed that this new tag was in many cases preventing the insect from flying.

Given the persisting issues, we eventually decided to move to vertical polarization and to a vertical "loop" tag in P1b (Figure 5D). To ease the mounting procedure the tag was placed on a rigid base of approximately 4 mm^2. This setup worked very well, providing several detections per flight and, in general, far better results than the previous configuration based on horizontally polarized antennas and tags.

For the last two prototypes, P2a and P2b, while still dealing with vertically polarized field, we introduced the more compact "J" tag (Figure 5E), characterized by two asymmetric branches (4 mm and 12 mm) with a diode soldered across the bend. The weight of this tag was approximately 15 mg, while the harmonic cross section σ_h (as defined in [25]) was estimated to 2 mm^2.

In addition to the tests on the shape of the tag, we also optimized the mounting procedure. We started with a strong commercial glue which required about 20 s to create a reliable bond between the tag and the specimen; in order not to stress the insects during this period and to prevent them from moving, a dose of carbon dioxide was necessary to anesthetize them. The amount of glue resulted to be a rather delicate parameter: it had to be enough to prevent the hornet from removing the tag, but not too much to obstruct the flight. Furthermore, the anesthesia seemed to worsen the recovery of the hornets, which appeared to be stunned for few minutes after their release. For these reasons, we finally tested a product adopted in orthodontics, namely TransbondTM XT (3M Unitek, Italy), which polymerized in few seconds using a polymerization Ultra Violet lamp. With this configuration it was possible to reliably mount the tag in less than 8 s without any sort of anesthesia; the hornets were captured in front of the hives, put in a Falcon tube, immobilized with a cotton swab and a pair of tweezers, and loaded with the tag (see Figure 5D). This procedure had no impact on the hornet, which started to fly immediately after its release. We also noticed hornets equipped with the transponder preying in front of the hives several days after their capture, clearly indicating that the presence of the tag did not limit their daily routine.

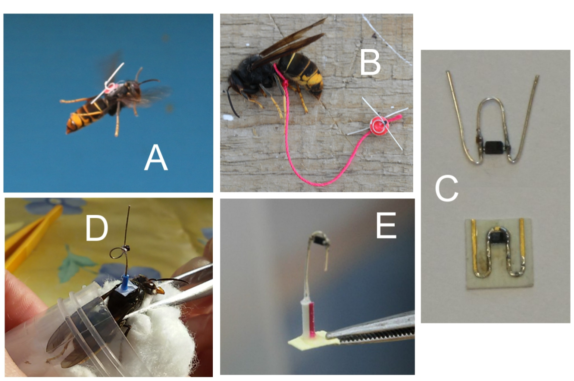

Fig. 5. Tag evolution in time. Horizontal "loop" (A), "X" (B) and "W" configurations (C) were tested for horizontally polarized antennas (P1a). Vertical "loop" (D) and "J" (E) configurations were adopted for vertically polarized antennas (P1b, P2a and P2b).

C. The RX module

For all prototypes the RX module was based on an ad hoc design adapting commercially available components. In the P1a prototype, the 18.82 GHz signal received by the antenna was first amplified and then mixed with the local oscillator in a low noise down-converter block (LNB) usually adopted for satellite reception (9000HXO3B-BN KA-BAND DUO LNB from NORSAT). The demodulated signal was afterwards filtered in the working band of the radar and then rectified by a logarithmic detector. The so obtained signal was then digitized, buffered and processed by a high performance Digital Signal Processor (DSP) board. To conclude, the output data were transferred to a laptop for the real time graphical visualization. The RX antenna was a microstrip cascade patch array working in horizontal polarization with a maximum gain of 27.4 dBi, entirely designed and optimized by us.

The RX system of P1b was conceptually made up of the same modules of its predecessor, with an accuracy of 1.5 m in range and 0.1 degrees in angle, out of a raw radar resolution of 15 m. Similarly to the TX launcher, also for the RX antenna we designed and manufactured a vertically polarized slotted waveguide (WR51 with 50 slots) with a maximum gain of approximately 27.3 dBi (see Figure 6. We also designed two alternative solutions for the circularly polarized option, namely a microstrip antenna and a slotted waveguide. As for the TX antenna, we decided not to proceed on with this configuration due to the low efficiency.

With the introduction of a new TX module, also the RX chain was properly modified in P2a. The received signal was collected by the RX antenna mounted on top of the TX one. Directly connected to the RX antenna and powered by a dedicated battery rotating together with it, there was a high gain low noise amplifier (LNA, from BZ Technologies). The signal was then passed through the dual channel rotary joint and sent to a BPSK coherent I/Q demodulator. The demodulated I (In-phase) and Q (Quadrature phase) signals were digitized and delivered to an FPGA processing board.

P2b shared the same receiving chain with a more directive 30.6 dBi antenna (80 elements slotted waveguide). In addition, the LNA was no longer located right after the antenna, but packed with all the other hardware downstream of the rotary joint; as a consequence, the dedicated battery was removed from the rotating top of the radar. In general, the main TX and RX upgrade of P2b was the assembly itself: all microwave components were singularly packed in "connectorized" boxes and then grouped together into a waterproof rack. Similarly, both TX and RX upgraded antennas were covered by radome to be waterproof.

D. Advanced radar analysis

In P1a and P1b the pulse leakage from the TX transmitter triggered the RX module to capture and elaborate real time data. To increase the signal to noise the DSP averaged 16 subsequent pulse sequences and executed a correlation in range. A Moving Target Identification (MTI) algorithm was also developed to filter out pulse leakage and clutter echoes, which are quite strong especially from buildings, vehicles and metallic objects in general. The received signal was then sampled at 100 MSPS with about 3600 pulse sequences

Fig. 6. TX (bottom) and RX (top) vertically polarized antennas used in P1b and P2a prototypes. Both launchers are slotted waveguides equipped with metallic flanges to shape the radiated field on the vertical plane.

captured per revolution, for an accuracy in range of 1.5 m (out of a raw radar resolution of 15 m) and in angle of 0.1 degrees.

Due to the low efficiency of passive transponders, high range resolution and high sensitivity are crucial for this application. Unfortunately, the main limitation to achieving high sensitivity with short duration pulses is that a high peak power is required for a large pulse energy. This problem was solved in the P2a and P2b prototypes, without losing the short pulse advantages, with the help of the so called pulse compression: a transmitted long pulse divided into 1024 sub-pulses was modulated in phase (binary phase coding) according to a Golay sequence, and the received echoes processed with a proper matched filter. An FPGA hosted the developed firmware responsible to command the modulator and to correlate the received signals with the transmitted sequence in real time, 1000 times per second. The results of the correlation process were sent through an Ethernet connection to a standard laptop PC for the high level processing and output visualization. The core of the high level processing was the Doppler shift estimation implemented by performing a Fast Fourier Transform (FFT) per each range-angle bin along a certain programmable number of pulses. This allowed to further suppress the local leakage and to better discriminate between fixed (the ones with large radar cross section) and moving targets. An adaptive threshold was also raised to remove moving clutter such as that from weather, birds or waiving vegetation. The system stored all the transponders positions for further replay and geo-localization. A complete graphical user interface permitted to set all the radar parameters and to choose output formats.

III. Results

In P1a the maximum detection range was estimated to 120 m. On-field tests performed in 2015 nearby Dolceacqua, in the inland of Liguria, few kilometers from the France border, confirmed this value and demonstrated all the above mentioned limitations of a horizontally polarized signal. The success rate of the tag mounting procedure on the insects was also rather poor, with only about half of the tagged hornets being able to fly after release.

An encouraging progress was observed in 2016 with P1b prototype, tested again in Dolceacqua. There was a slight improvement on the maximum detection, raised to about 150 m. The main upgrade was documented both in terms of success rate of the tag mounting procedure (almost all the tagged insect were recorded by the radar and the mounting itself was faster) and in terms of number of continuous tracks recorded in a limited amount of time (less than one hour). The P1b prototype was also moved to different locations and a single trace was observed 300 m from the starting position, demonstrating the possibility to follow the hornets track in steps up to the nest.

In 2017 the P2a prototype was extensively tested in order to guarantee the reliability of all its components from the engineering point of view. A 470 m maximum detection was recorded on flat terrain (with a tag mounted on a pole) and the first hornet nests were eventually located at the end of the season in Dolceacqua. In 2018 the prototype was routinely adopted for on-field campaigns in Liguria, from June to the end of October. Several nests were located, both in urban and rural environments. All traces were recorded and stored to provide a better insight on the hornets flying paths and daily activities.

In 2019, the last P2b prototype was operated few times, providing again continuous and reliable traces, as documented in Figure 7.

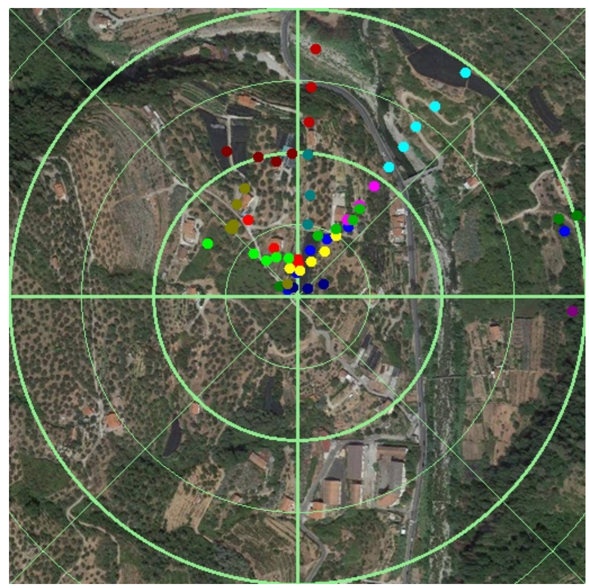

Fig. 7. Hornet traces recorded with the P2b prototype in 2019 close to Dolceacqua.

IV. Conclusions

Insect tracking with the help of harmonic radars is a 30 years long practice, even though performed in quite convenient flat environments. In this paper we describe the evolution, from 2015 to 2019, of a new harmonic radar which can be operated also in harsh environment, allowing to track miniaturized lightweight passive tags installed on insects flying in a hilly and woody landscape.

The usability and the flexibility of the system (above all the last P2a and P2b prototypes) were satisfactory, as demonstrated by daily operations; the last version required approximately 5 minutes to be installed (and uninstalled) by two operators. The radar did not need the constant presence of an operator when active, allowing him/her to capture and tag the insects instead. One hour was usually enough to have a clear indication on where to move the radar next in order to get closer to the hornets nest in a few steps. This time could be reduced to 30 minutes or even less in case of more than ten tagged insects. A nest could be located within the 7 m resolution of the radar in the most favorable case, i.e. when it was in line of sight from the radar position. Our harmonic radar could be used to narrow the search area if the nest was well hidden within a forest.

The main limitation was the need for a vehicle to move the radar equipment from one location to the next one; the overall weight (the radar and the trellis) was about 50 kg, which prevented its positioning too far from the vehicle and hence from a road or a trail. The possibility to use the radar directly from a motorized vehicle and the design of a lighter portable unit are possible solutions to reduce these limitations.

This radar system was adopted as one of the measures to eradicate *V. velutina* from Italy, but it can be adopted as part of an early-warning strategy valuable in countries where this hornet can still be stopped before it gains a foothold. As previously claimed, the radar usage can be extended to many other applications involving the study of the biology of other insects and animals of limited size, such as bees, bumblebees, butterflies, dragonflies, moths, etc. The only requirement is the capability of carrying a small and lightweight transponder (about 15 mg of weight).

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