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Review

Novel Physical and Computer -Based methods for Adult Mosquito Pest Control and Monitoring

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Abstract

Mosquitoes are a global danger with high impact on human health. They have a robust host seeking strategy and unusual flight dynamics. This review gives a short overview of the main threats of these tiny insects, points out its position in zoological model animals and discusses novel physical and computer-based methods for mosquito identification, killing, and monitoring. The focus is on applications using imaging systems, acoustical detection, and lasers in combination with advanced signal analysis and processing. Furthermore, recent crowd data acquisition and theoretical modeling of human behavior and mosquito population/vector dynamics are discussed. The conclusion show, how future pest control strategies and devices can be optimized to end up in cost-efficient products for the broad market.

Introduction

Mosquitoes - a global danger

A source of danger must not be big to have a high impact on human health. Blood-seeking flight insects are one of the most dangerous animals on earth. More than 500 million people are currently infected with mosquito-borne diseases, and more than 3 million people die every year from these infections [1]. In addition, currently half of the world's population, about 3.5 billion people, is now at risk for infection from mosquito-borne diseases. Taking into account, that global warming expands global occurrence including warm countries in Europe it is easy to believe that without new interventions, infections and deaths are likely to rise.

There are three major reasons for the great danger of mosquitoes. First, female mosquitoes require a blood meal for proper development of their eggs and evolution gave them the tools to do this successful by use of their specialized mouth which enables them to puncture the human skin. Second, several mosquitoes are anthropophilic, meaning that their preferred host is humans. And third, mosquitoes carry a number of viruses or parasites without being affected themselves. A minor side effect of their host-seeking behavior is that they keep us from peaceful sleeping because even just their bites are harming and their hovering sounds make us awake. Altogether, the mosquito is a highly effective and mobile agent for transmitting dangerous diseases among the human population affecting health in multiple ways. In front of this background; it is not surprising that mosquitoes are in the top ten of zoological model animals in the past five years. In detail, Mosquitoes with *Anopheles* and *Aedes* are in front of *Drosophila*, Bee, Zebra fish and Chicken (Table 1). To understand how to protect humans and farm animals from mosquitoes, zoologists and computer scientists did a good job by characterizing the behavior and morphology of these insects (and humans).

Rank	Animal	Hits		Rank	Animal	Hits
1	Mouse	1796		23	Bee	234
2	Fish	1757		24	Zebrafish	214
3	Insect	1529		25	Chicken	202
4	Rat	1243		26	Cattle	179
5	Bird	1160		27	Moth	178
6	Fly	724		28	Dog	192
7	**Mosquito**	**613**		29	Reptile	157
8	*Drosophila*	543		30	Snake	155
9	Beetle	449		31	Monkey	152
10	Rodent	448		32	Catfish	139
11	Lizard	317		33	Sheep	136
12	***Anopheles sp.***	**313**		34	Carp	132
13	Frog	310		35	Butterfly	127
14	***Aedes sp.***	**309**		36	*Trematode*	127
15	Worm	301		37	*Xenopus*	123
16	Spider	299		38	Helminth	122
17	Cat	293		39	Crab	121
18	*Plasmodium*	285		40	*Cichlid*	115
19	Bat	268		41	Earthworm	112
20	Snail	246		42	*C. elegans*	111
21	Tick	245		43	Rabbit	109
22	Ant	235		44	Turtle	101

Table 1: Top 44 most frequently used animals/animal groups in zoological research literature from 2012 to 2017. Word frequencies in Title, Abstract, and keywords in a PubMed search with the general search term "zoology" were analyzed and screened for animal names. Mosquito relevant words are highlighted in bold. The text corpus for this analysis consisted of 23627 database entries.

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Mosquito host seeking

Host-seeking in mosquitoes consists of at least four compounds of sensory input: Detection of odors, carbon dioxide, heat and optical clues [2-4]. Host-seeking behavior is a complex process and these animals seem to switch between several navigation strategies depending on signal quality, which in turn is influenced by the distance from the host and possible obstacles in the environment [4]. The independent and iterative nature of the sensory-motor reflexes renders mosquitoes' host-seeking strategy annoyingly robust.

Mosquito flight

Mosquito's (here *Culex quinquefasciatus*) exhibit unusual wing kinematics; their long, slender wings flap at remarkably high frequencies for their size (>800Hz) and with lower stroke amplitudes than any other insect group [5]. Their maximum flight speed reported is 4.3 km/h or 120 cm/s in West African Mosquito's [6]. With a weight of about 2 mg, they can survive an impact of the raindrop with 50 time's higher mass due to their super hydrophobicity [7]. This allows them to fly even in the rain. Although the animals have strength due to their robust navigation and hydrophobicity, they also have weaknesses given by their low mass and limited energy reserves. This makes them quite sensitive to higher wind speeds.

Mosquito pest control

Mining in the PubMed Database reveals about 48600 publications using "mosquito" as the general search term, and 1618 by narrowing the search to "mosquito" and "pest control". Looking at the majority of publications, three major mosquito control strategies exist 1. Physical protection, like barriers or nets. 2. Chemical protection including insecticides, repellents and attracting agents with traps. 3. (Molecular) biological protection including population control by using sterile males or competitive attacks with genetically modified individuals with an impaired sense of smell abilities to find their hosts. While the third strategy is some kind of a new generation of mosquito control currently under investigation, chemical and physical control is state of the art of current protection [8,9]. The major weakness of chemical protection is the fact that chemicals decay in concentration over time and need to be replaced in a repetitive manner. The weaknesses of physical barriers are annoying restrictions to the humans.

Novel physical and computer-based methods for mosquito pest control

In the last decade, a few studies and innovations have been published which sometimes read as being science fiction stories. It is an upcoming trend to design physical pest control strategies which use imaging systems (or other signal analysis) to identify flight insects in order to detect and monitor them and to investigate their behavior. These methods apply components like microphones or other force perception sensors, light and light detectors. In some cases, even lasers are used to apply critical energy amounts to the mosquitos without harming humans. One of the major goals of these novel methods is to reduce energy consumption (e.g., to make them more suitable for solar powered applications). Another goal is to increase trapping and killing efficiency of only insects being critical to human health instead of killing insects in general. The spectrum of strategies varies from the improvement of existing physical methods to the invention of new pest control devices, which are sometimes inspired form technologies used for military surveillance, enemy identification and defense systems. Big-data analysis of crowd-based data acquisition can help to establish prediction models to optimize these methods.

Laser-based killing methods

The first idea using this strategy was a device invented by the astrophysicist Lowell Wood is a prolific inventor listed on 1,667 U.S. patents as of December 29, 2017 (Results of Search in US Patent Collection db for: (APT/1 AND IN/(Wood-Jr-Lowell$ OR Wood-Lowell$)). At a brainstorming session in 2007, to think of solutions for malaria, Wood, one of the architects of the Strategic Defense Initiative (SDI) suggested designing a system to kill mosquitoes with lasers. Soon after, the idea was followed up by many scientists at Intellectual Ventures and mosquitoes were being shot down within a year [10]. The original idea incorporates laser technology that stems from the SDI, scaled down to insects. The so-called "Mosquito Laser" is a prototype which uses an imaging CCD Camera in combination with low power laser illumination (or LED) and a retroflective material (mounted at the other end of the photonic fence) to detect mosquitoes. Another high power laser then kills the detected target by physical disintegration (for illustration see http://www.intellectualventureslab.com/work/photonic-fence). Although the original idea was to deploy this device in third world regions the high energy consumption and huge size will suggest it to be more suitable for agriculture or industrial use than for household [11]. So today, seven years after the presentation of this ground breaking technology in a TED talk "Could this laser zap malaria?" We are still waiting on the Laser-Shooting Mosquito Zapper [12]. Currently, these devices are still in the prototype stage. Journalistic texts like "What happened to the mosquito-zapping laser that was going to stop malaria?" or "Where's Our Laser-Shooting Mosquito Death Machine?" Very often forget that sometimes it needs a decade to wait for the technology to catch up that make an innovative idea to an idea whose time has come [13,14].

Using lasers to kill mosquitoes can be dangerous for humans and environment as well. To keep the risk to burn the wrong things low laser positioning and beam properties are important. An experimental setup, which uses consumer optics (telescopic macro lens (Canon EF 180mm f/3.5 Macro) coupled to a beam splitter with a laser and a CCD camera co-aligned seemed to be suitable to investigate these parameters. With a setup like this, it was possible to determine the right laser spot size, wavelengths, power and pulse dosage suitable to kill a mosquito [15]. An invention that circumvents possible collateral damages are a device with one or more rotating circular laser pattern projectors in a perforated housing [16]. This device is similar to the well-known UV-traps but instead using use a high-voltage grid inside the housing it uses laser light to kill the insects. Compared to the photonic fence this device is smaller in size, being more suitable for household use.

A completely different attempt to kill mosquitoes is inspired by biomedical applications which target abnormal cells with nanoparticles. After that these cells can be eradicated by application of light. This method has been successfully transferred to whole organisms like *C. elegans*, mosquitoes and other insects which have been fed carbon nanotubes, gold nanospheres, gold nanoshells, or magnetic nanoparticles. These organisms can be injured with laser energies that are safe for humans [17]. This strategy seems to be capable to reduce the use of toxic agents in pest control of species where feeding of these particles is possible. An evaluation of the environmental impact of spreading out nanoparticles compared to toxicants should be topics of future publications.

Light-based trapping methods

Light traps are well-known devices for catching and killing flight insects. A huge disadvantage of these apparatus is the high energy consumption which makes them in some cases unsuitable for third world use. Today, fluorescent tubes have been replaced by space-saving Light Emitting Diodes (LED). Unfortunately, LEDs have a worse energy efficiency compared to fluorescent tubes. Recent studies demonstrate that catching efficiency did increase by 250% when the LED was Pulse Width Modulated (PWM). Furthermore, PWM allows for a reduction of energy consumption by 25% and enables these devices to be solar powered [18]. Although the underlying neurophysiologic mechanisms that trigger this higher attraction are not understood, it can be speculated that modulating pulse width is another interesting parameter to be tuned in these systems. Findings from this research may be transferred to other light sources like lasers as well.

Audio and light-based identification methods

Mosquito's have a sensitive acoustic perception and there are numerous studies which explore the role of acoustic signals for interspecies communication. These animals seem to have a complex auditory processing which is required for different interesting behaviors [19]. For example sex recognition and wing beat frequency matching or male-specific rapid frequency modulation [20,21]. This suggests that analysis of wing beat frequency modulation can provide information about species and behavior by using sensitive microphones for mosquito monitoring. Examples for an innovative product that utilizes acoustic signal analysis are smart phone apps or surface acoustic wave sensor [22,23]. It is very probable that different mosquito (or other flight insects) species have developed their own characteristics for communication which in turn makes it very probable that they can be identified by their characteristic acoustic "fingerprint". One example that utilizes this is a low-cost system to discriminate flying insect. This system consists of a low-cost laser line device and a line-shaped photo detector and can be called a pseudo-acoustic detector. When an insect passes this light barrier, the motion dynamics (wing beat frequency and speed) are detected to calculate a power spectrum [24,25]. From these data, the system can be trained to identify the insect or machine learning can do this [26]. These techniques may improve flight insect monitoring in the lab scale and possibly in the future in the field scale.

To make a more detailed analysis of mosquito communication it is important to understand how they behave in the crowd. Industrial CMOS camera systems and digital image analysis have developed to powerful big data collection devices. With an open source development like a low-cost collective behavior quantification it is possible to not only focus on the tracking of individuals but on the behavior of a whole swarm of mosquitoes [27,28]. The next logical step will be to combine fast wide-field image acquisition and analysis with high-resolution pseudo-acoustic detection. This would combine the strength of high-resolution single animal behavior and swarm behavior at the same time.

Network-based acquisition of human behavior and vector occurrence for advanced modeling

The efficiency of pest control can be improved by a deeper understanding of human behavior and vector dynamics. Growing mobile networks and the omnipresence of smart phones is an ideal basis for the acquisition of crowd data. With this data, it should be possible to understand and later on to train humans to behave better dependent on the current vector dynamics situation [29,30]. The prognosis on vector occurrence is based on the analysis of big data from mobile networks. There are some field tests and case studies which may be the basis for a more consistent and easy-to-use crowd based data acquisition to form regional and global models [31-34]. Even in regions where mosquitoes are not that dominant in the statistics of health sciences citizen science projects are started to create a map for monitoring the distribution of invasive mosquito species in Germany and the USA (http://www.citizenscience.us/imp/) [35].

The dynamics of a mosquito population depends heavily on climatic variables such as temperature and precipitation. There are theoretical models that show effects of rainfall on *Culex* mosquito population dynamics [36]. Maybe these models can be supported by field data based on mobile data acquisition in the future.

Conclusion

Mosquito's have developed a robust navigation system based on several sensory systems which enables them to show complex behavior and makes them very successful in their ecological niche. Advanced technologies reviewed above analyses their strategy and are enriching our knowledge about how to economically control them without harming humans or other species. Without a doubt, these new technologies and more detailed knowledge about the physiology of mosquitoes will lead to new innovative products.

Although there are already smart ideas to enhance mosquito pest control, most of them are still in the prototype stage. One of the main problems is that different mosquito species behave in different ways and you cannot control them with a single strategy. In the end, it is always the amount of money needed that drives these decisions. The use of insecticides is not only bad for the environment but also expensive. New technologies can target mosquitoes in a more precise and more economical way but the technology itself is still very expensive. In several interviews with key researchers from Intellectual Ventures, it is always argued that most of these high-tech pest control systems work, but are too expensive for the broad market.

To design a product for the broad market it should be a good idea to make future pest control systems adaptable to different species and different geolocations. This can be solved with "deep learning" technologies like mosquito detection with neural networks and/or big data analysis of crowd data acquisition [37,38].

Good prediction models should be supported by big data sets and in the recent years, many countries have recognized that citizen science projects can be a powerful tool to collect them. Future pest control strategies can be optimized by the use of these models.

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