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BIONICS OF VISUO-MOTOR CONTROL

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I. INTRODUCTION

In matters of visuomotor intelligence, there exist innumerable lowly earthly creatures which can easily outdo human beings, however hard we may try. For this reason, a strictly anthropomorphic approach may well be out of place when designing tomorrow's *seeing vehicles*, which will have to behave swiftly and efficiently in unstructured, unknown and hazardous environments. Designers of autonomous vehicles wishing to profit from previous successful and thoroughly tested achievements may have much to gain by casting a sidelong glance not only at human cognitive processes but also at the sensori-motor control systems of humble but highly skilled creatures such as insects, arachnids, and crustacea.

In a recent review (26) we presented some data on the art of signal processing in the cockpit of the fly. At our laboratory, flies are viewed as perfect miniature, self-propelled and cordless 'vehicles' (7), which are able to use vision to navigate swiftly and land safely in the most unpredictable, obstacle-cluttered environments. These sighted agents take the bearings of obstacles and avoid them without resorting to any sonars or laser range finders. They carry their own energy resources, and process their sensory signals onboard, without having to trail behind them any cumbersone umbilical connecting them to a supercomputer and a power supply. There exist so far no visually guided artificial agents which are able to match the real-time visuomotor prowess of the fly. In the major engineering challenge which consists of designing sighted vehicles capable of steering their way quickly through complex, unpredictable environments, the successful fly guidance system may provide some unexpected solutions. Surely it is high time that this

little aircraft, which can be so objectionable in many ways, stopped adding insult to injury by doing what it does better than the present-day robots can.

Since 1985, in parallel with our basic research on the neuronal pathways involved in animal vision, our group has been developing sighted, self-guided mobile robots which make use of lessons drawn from the insect world*: lessons learned in neuroethology, lessons about the mechanisms underlying signal processing in nervous systems, and lessons about the optical and neural architectures. The aim is to fuse ideas from biology and robotics, with potential benefits to both fields - since many of the tasks to be performed are similar.

Here we report on the design and construction of a fly-sighted demonstrator, i.e., a robot equipped with a compound eye comprising an array of fly-inspired 'Local Motion Detectors' (LMD's). This bionic attempt to incorporate into an 'auto-mobile' the working principles of specific neuronal circuits - those we previously analysed in the visual system of the common housefly (31) - ended up with a ten kilogramme, self-driven terrestrial vehicle capable of moving towards a luminous target at a fairly high speed (50cm/s, i.e., about two body lengths per second) while avoiding any unpredictable obstacles encountered on the way. This account summarizes the philosophy behind our work on these lines and readers can refer to the original papers for further details (60,29,30,50,54). This account is largely based on a paper presented at the 3rd Bionics Congress in Mannheim, Germany, in june 1996 (30'). The authors of more recent studies have used a similar, biologically inspired approach to the visually-guided, reactive navigation of an artificial agent (15,63,67,10). The physical robot we arrived at is unique, however, in that it operates using the parallel, analog method of signal processing, favoured by Nature.

Our approach fits the general framework of 'active perception', in that an *ad hoc* motion of a sensor is used to constrain the inputs and reduce the computational burden involved in perceptual tasks (4,2,3,1). Readers interested in the general design of - seeing or not seeing - reactive agents ("animats") and behavior-based AI can refer to the proceedings of several recent conferences on this subject (69,52,19,53,34,11).

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* *These and other lessons from the insect world are reported also in the paper "Engineering Applications of Small Brains", by N. Franceschini, FED Journal (Future Electron Devices), N°7, February 1997*

II. PRODUCING A SIGHTED MOBILE CREATURE

As early as 1867, von Helmholtz discussed the possibility that humans might use *motion parallax* to assess the three-dimensional layout of the environment. For some reason, however, the idea took about 100 years to mature, perhaps because it took nearly 100 years to realize that the vertebrate visual system indeed includes a set of smart sensors called "motion sensitive neurones" - as postulated by Exner in 1894, see Fig. 2 in ref.31 - which are able to determine the retinal slip speed at various azimuths and elevations in the visual field, and thus to provide their host with an estimate of the *optic flow field* (cf. 35,36,48,56,44,40,42,45,72).The idea that insects too can use motion parallax and take advantage of the optic flow field to take range of objects and navigate was suggested early on by Exner (22), but actually proved only quite recently in some fine sets of experiments (71,12,16,49,43,66) (see also the reviews: 73,9,41,68,14).

We have described how we analysed the basic working scheme underlying the housefly's directionally selective motion sensitive neurones (62,31,26). This research involved carrying out microelectrode recordings on the electrical activity of a specific motion-detecting neurone, called H1. The sensitivity of this neuron to directional motion relies on the pooling of multiple signals from smallfield units called 'Elementary Motion Detectors' (EMD's, cf. ref.9), also called 'Local Motion Detectors' (LMD's, cf ref.14), which all project to its dendritic arbor in a retinotopic manner. To assess the functional properties of one such LMD, we used a specially designed stimulator, a hybrid between a microscope and a telescope, which served to illuminate two neighbouring photoreceptors cells *sequentially* within the same facet, thereby mimicking a micromotion occurring in the visual field (62,25,31).

By 1986, we had built the first optronic replica of a fly LMD, which was capable of processing its two input signals stage by stage, in the analog mode, with similar time constants and nonlinearities to those observed in the live animal. Using a 'surface mounted devices' technology, we had more than a hundred such motion detectors made in the form of minute electronic boards (each weighing as little as 6 grammes), which we used to produce a whole compound eye designed to equip a mobile robot and steer it through a cluttered environment, by making use of the optic flow.

The functional scheme on which this robot was based drew heavily on our knowledge of the fly's visuomotor behaviour. Fast motion picture analyses and experiments in a flight simulator have shown that the cruising fly maintains a near constant angular body- (and probably eye-) orientation, interrupted by

saccade-like turns of various amplitudes, which are performed at a high angular velocity (13,47,75,76,38,70,14). We took this to be a strategy adopted by the animal to reduce the optic flow field to its *translational component* (cf.5,58). Here the interesting basic principle involved is that only the translational component of the optic flow field generated by an agent's movement can convey a depth map of the extra-personal space (44,61) (Fig.1)

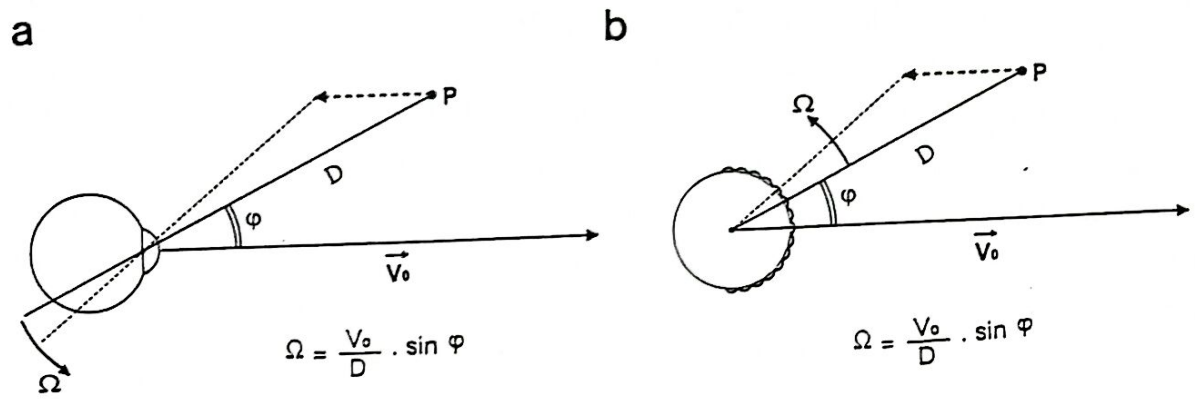

Fig. 1: Using the translational optic flow field to avoid obstacles. To an observer (human, fly, robot, etc.) with a camera eye (a) or a compound eye (b), which translates to the right at speed Vo, a contrast point such as P located at azimuth φ seems to move to the left at opposite speed -Vo. If the visual system of the observer has a means of determining the angular speed Ω at which P seems to be turning, then the observer can gauge the distance D to the contrast point (via the simple formula given here, cf 74) - and then produce a suitable steering manoeuvre to avoid it .

In the same way, our robot proceeds by performing pure translations (during which it collects the relevant visual information 'on the move'), which are interrupted by fast steering actions. The numerous LMD's built into the eye of the moving robot act like so many miniature teledetectors, assessing the distance to any contrasted obstacles encountered as it travels along.

Since we were designing a terrestrial robot capable of moving on a single plane only, we decided to simply equip our automaton with a horizontal ring of facets, the visual axes of which would all cross at a common point: the centre of curvature of the eye - which was also the centre of the (circular) robot (Fig.2). This ring contains about as many facets (around 100) as the number which can be counted on a horizontal cross-section through both eyes of a fly, and the visual field afforded thereby is correspondingly very large. For reasons having to do with the geometry of the optic flow, we provided this eye with a resolution gradient such that the spatial sampling step grows according to a *sine law* as a function of the eccentricity (60,30). This specific non-uniform

sampling procedure 'compensates' for the sine law inherent to the optic flow field (cf. formula in Fig.1) and thus ensures that any contrast point located inside a *circle of vision* of radius R_V will be detected upon translation by a step of length ΔL (Fig.2). It should be recalled here that a resolution gradient exists in the fly as well, whose eye is more acute frontally than laterally (6,13,24). The introduction of a sine gradient into this 'centred eye' would lead, however, to an infinitely small interommatidial angle along the heading direction. Therefore a 'deadzone' of +/- 10° was provided around the frontal pole of the optic flow field. This deadzone was covered by two small additional sets of LMD's that were off-centred and symmetrically positioned on each side of the vehicle (Fig.2) (60) .

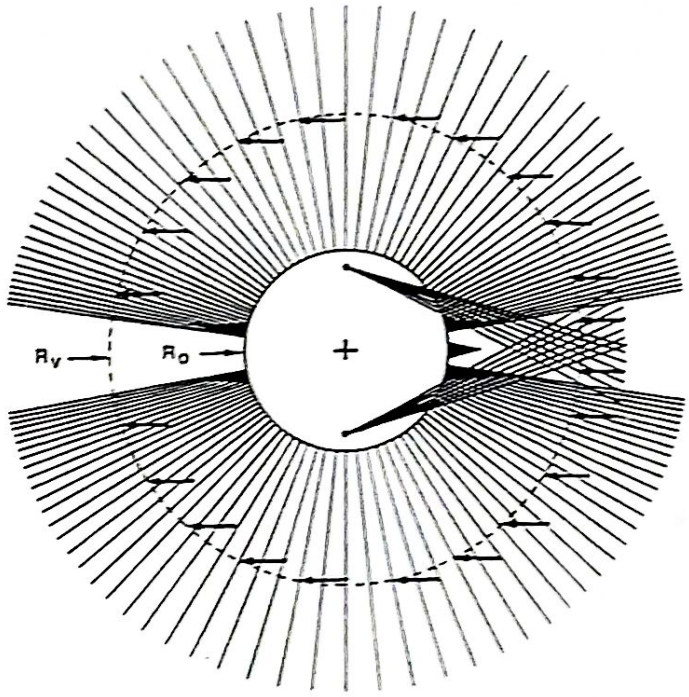

Fig. 2: Complete set of visual axes of the planar robot's compound eye, as seen from above. Sampling of the visual environment is performed in a nonuniform way, with a sine-law gradient in interommatidial angles from the anterior (and posterior) to the lateral part of the eye. Two separate sets of local motion detectors (LMD's) are off-centred and so aligned as to cover the +/- 10° 'deadzone' around the heading direction (frontal pole of the optic flow field)

Once the photoelectrical signals have been processed in a logarithmic amplification stage, as in the fly, the next stages consist of detecting the contours of obstacles and measuring the time elapsing between the stimulation of any two adjacent facets. Angular velocity thresholds are then set in such a way that nearby contrasts are given priority over those which are farther away from the robot. The motion detecting array thus generates a map of obstacles, which are expressed in polar coordinates in an eye-centred frame of reference at

the end of each translatory step. This map is immediately merged with the information about the azimuthal direction of the target (an electric light), before being delivered to a 'motor interface', which then specifies in Volts the new steering angle required to bring the robot one step further towards the target while avoiding the obstacles detected during the previous translation phase.

The trajectory of the robot thus consists of stereotyped translation steps ΔL in length which serve to acquire visual data (Fig.3). During each translation step, the robot surveys the environment with its numerous local motion detectors, and updates its own local picture of the outside world. This picture is immediately obliterated once the obstacle has been left behind. At the completion of each translation step, the next course to be steered is immediately given by the output from the motor interface, and this immediately triggers an (open loop) ocular and steering saccade of appropriate amplitude in the appropriate direction. During the actual steering manoeuvres, vision is disconnected because the ensuing *rotational optic flow* is not relevant to the range of obstacles. Vision is not restored until the appropriate *translational* speed is reached again. The elementary translation steps ΔL are tacked together at a high speed compatible with the parallel, analog mode of processing used. No stop occurs at the end of a translation step if no steering command is issued, i.e., if no obstacle has been detected by the LMD array.

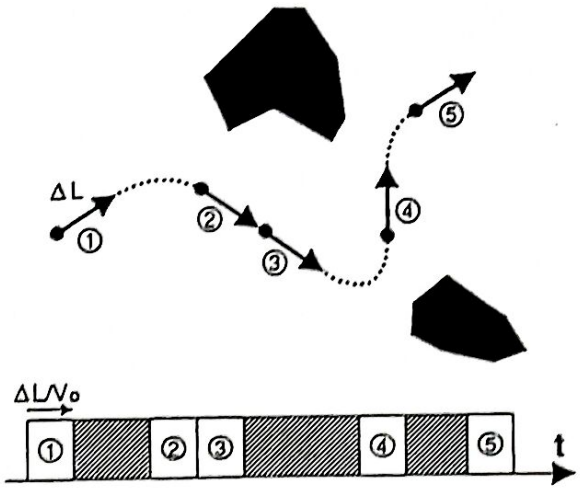

Fig.3: Locomotory mode of the robot showing the pure translation phases (1,2,3,n), performed at constant speed Vo and interrupted by steering manoeuvres the duration of which (hatched) depends on the steering angle.

The architecture of our visuomotor control system is reminiscent of Brooks' layered structure called 'subsumption architecture' (8). It differs from the latter in one major respect, however, since it has no enabling or disabling 'switch' deciding which of the two 'behaviours', target pursuit or obstacle

avoidance, should be dealt with by the control at any given time. There is no such distinction between two 'behaviours'. Instead, a *graded fusion* permanently occurs between the visual signals giving the *bearings* of the obstacles and the *direction* of the target. This kind of 'multisensory fusion', which takes place on a short-lived local 'motor map', ensures that the next heading direction will be the nearest possible to the target direction while avoiding the 'forbidden zone' computed onboard the robot on the basis of all the obstacles detected during a given translatory step.

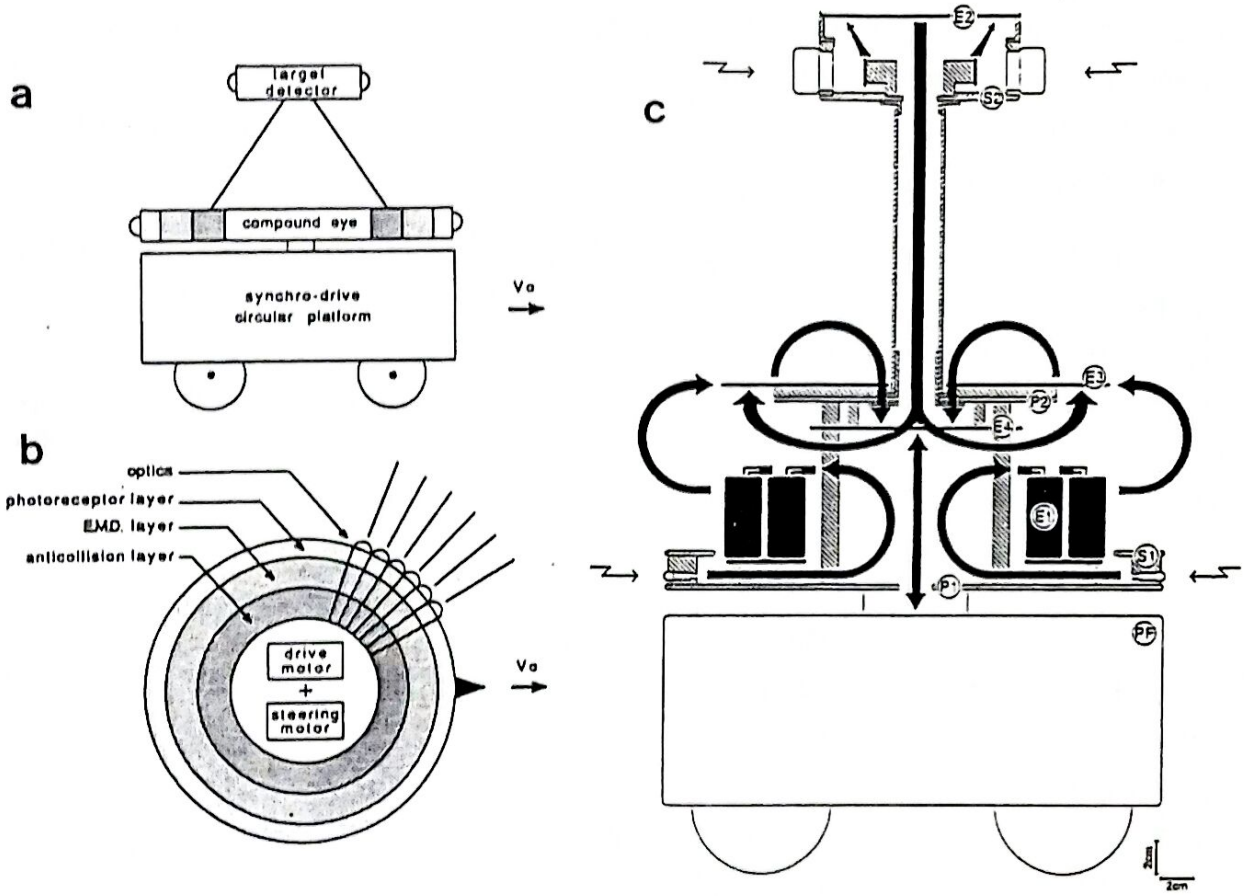

Fig. 4: The mobile robot is essentially equipped with a panoramic compound eye in charge of collision avoidance and with an accessory visual system (target detector on top) that constantly surveys the horizon (above all obstacles) and constantly informs the vehicle about the direction of the target light. The compound eye and the target detector are mounted onto a neck which is integral with the steering of the three-wheeled synchro-drive mobile platform (a: vertical cross section, b: horizontal cross section through the compound eye). (c) Signal flow onboard the sighted robot: the optical signal received by each ommatidium is guided to individual photodiodes by means of a light guide. Each one of the numerous miniboard E1 participates in local motion detection. The LMD's outputs drive the "fusion board" E3 (layout in Fig. 6), which also receives the numerous inputs from the local processor E2 of the target seeker. The (analog) output of the fusion plate drives the servosystem E4 that controls the drive and steering motors.

Our fly-sighted demonstrator (Fig.5) has shown that a compound eye equipped with only a hundred or so motion detecting neurones suffices to steer a vehicle safely and speedily through an unpredictable visual environment. The environment where it can dwell is textured with vertical stripes having random widths (in the range 5cm to 25cm) and random contrast (in the range O.15 to O.75). Alternately it can consists of cylindrical, randomly arranged posts. The collision-free paths taken by this robot between these posts provide evidence that an elementary but fast visual guidance system can be achieved without any symbolic representation and global reasoning about obstacles, without the need to resort to a permanent model of the world, without a central processing unit, without a CCD camera, without signal digitization, without any accurate and precisely matched visual sensors, and without any particularly large memory resources.

In comparison with 'main stream AI' approaches to mobile robotics, one of the most original aspects of this system is the use it makes of the brainlike *parallel and analog* modes of signal processing. The main reason for choosing these modes was the expectation that in practising Nature's way of doing things, and in fighting on the same ground, we might perhaps learn more about the advantages, constraints and adaptability of this mode of computation, and discover how it enabled the winged insects to survive in their highly complex natural environments for 350 million years. We therefore decided to do without any von Neumann-type architecture onboard the robot, and to restrict the use of computers of this kind to the initial simulation phases of the project. By incorporationg a second visual system into the robot, which makes it able to detect the direction of a target, we broke new ground on a territory where few attempts have been made so far in robotics, although animals' nervous systems do it all the time: using analog neural networks to achieve autonomous visuo-motor control. Fig. 6 shows the odd routing pattern that connects the thousands of analog devices that blend together the input signals from the compound eye and those from the accessory target-seeking eye, to eventually deliver a single analog output: the steering angle.

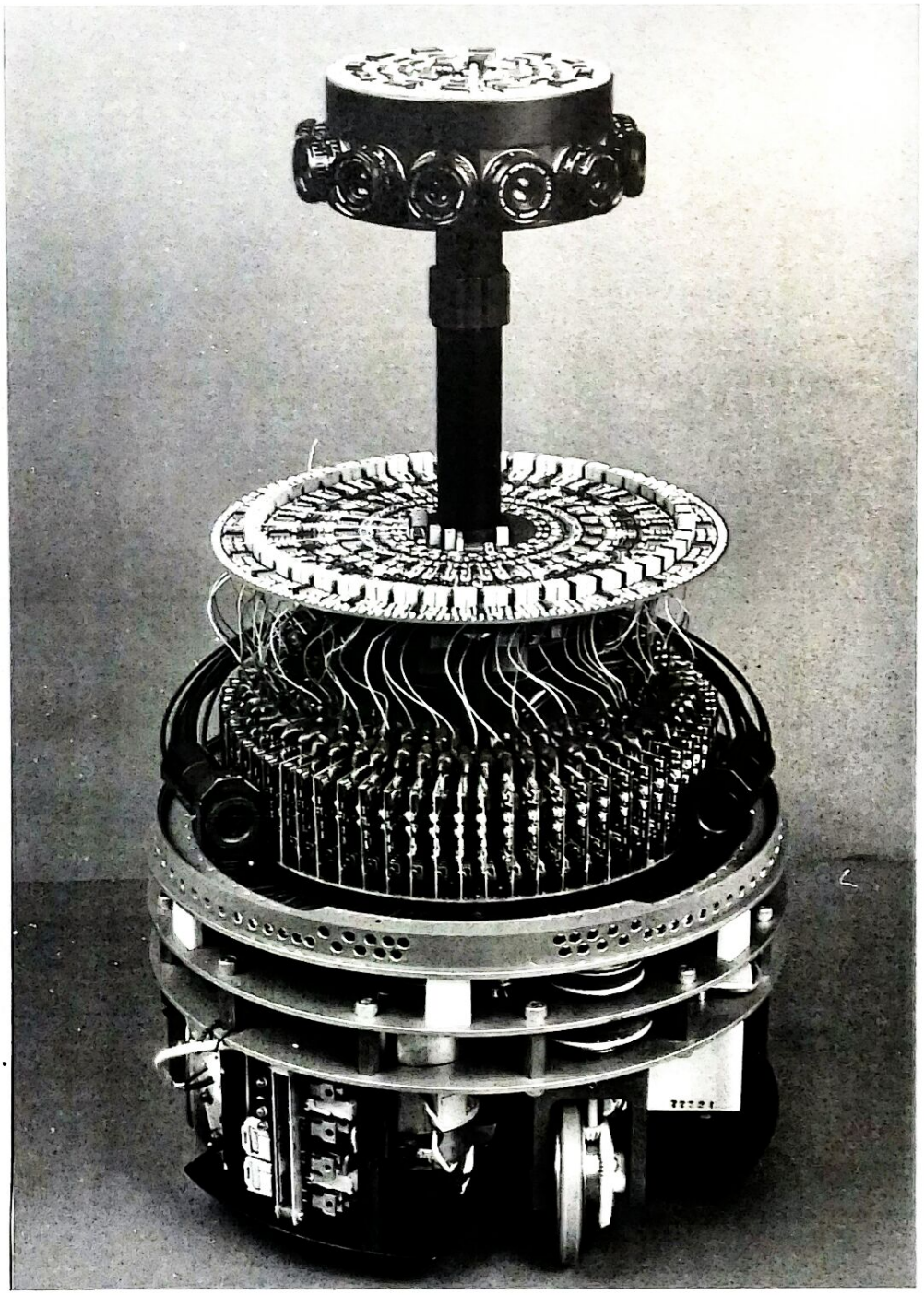

Fig.5: Biologically-inspired mobile robot. This 12 Kg, fully autonomous creature is able to move about at relatively high speed (50cm/s) by relying exclusivemy on vision. It avoids obstacles while móving towards the target. Its main visual system (seen here at one third of height) consists of a genuine compound eye (facetted eye), *which is built along the same principles as that of the fly, with a similar parallel and analog architecture. It features synthetic Local Motion Detectors, whose electronic signal processing reproduces in detail (time constants, nonlinearities....) that found in the fly compound eye by means of microelectrode recordings associated with single photoreceptor stimulation (25,31). The "accessory eye" seen on top is the target seeker that guides the robot to the light source.*

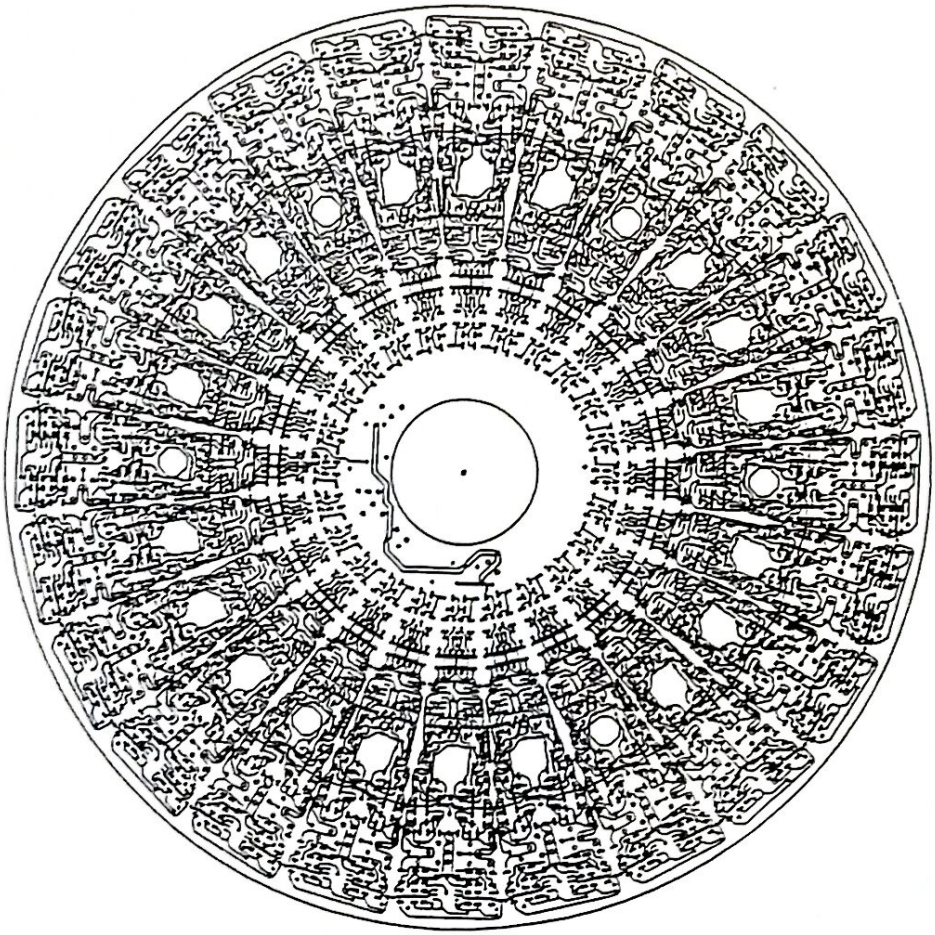

Fig.6: Routing diagram of one face of the printed circuit board that fuses the information about the obstacles and the goal. This six-layered board has about 200 parallel inputs (118 LMD's inputs, 96 inputs from the target seeker), and a single output, which gives in Volts the next steering angle required to reach the target while avoiding the obstacles. This side and the reverse side of the board are covered with thousands of analog, SMD devices of only four kinds: resistors, capacitors, diodes, and operational amplifiers. The rose-window-like pattern obtained here is reminiscent of the neural architecture of insect and vertebrate visual systems, and is very different from the architecture of a von Neumann computer. The mosaic organisation results from the numerous repeat units and their retinotopic projections (30)

III. FROM NEUROSCIENCE TO BIONICS, AND VICE-VERSA

Since this mobile machine was the concrete embodiment of knowledge acquired in neurobiology and neuroethology about insects' visual systems over the last 30 years or so, it incidentally yielded a wealth of physiological insights. The creature we ended up with was simpler of course than its biological forerunner, since we intentionally modelled only one of its aspects (navigation based on optic flow). Owing to its simplificatory nature, our approach shed some new light on sensorimotor processes in general and prompted us to perform novel electrophysiological and behavioural experiments on the fly that we would probably never have thought of otherwise.

One major physiological spin-off from this robotic approach has been the finding that, in spite of their fixed dioptrics, flies can in some cases display 'binocular vergence', a process that is currently being investigated at the laboratory using a variety of techniques (32,28,26). This process itself has generated several hypotheses, some of which have been tested via simulation. Adding a slight amount of vergence gaze control provided the key to having the robot automatically control its cruising speed depending on the density of the obstacles in its way . The keypoint is that a centred eye operating on the basis of motion parallax affords a *radius of vision* that automatically grows larger with speed (50). Now, the visual system described above can be enhanced if its two frontal, off-centred sets of LMD's (dedicated to vision near the heading direction, cf Section II) become off-centred in proportion to the robot's speed, so as to keep sampling the *circle of vision* (50). On the same line, simulation showed that motion parallax can be used to regulate the altitude and speed of a flying agent (54).

This type of research thus provides us with a real state of synergy between two disciplines which might seem *a priori* to be fathoms apart: the study of neurobiological mechanisms, and the production of artificial seeing agents. The notion that both natural and artificial visual creatures have to cope with similar difficulties raised by the complex world which they both inhabit, and the idea that the complex problems they have to solve may have a very limited number of solutions incite one to approach natural and artificial creatures on a common footing and to work towards a really multidisciplinary approach in the study of sensory perception and sensory-motor control.

IV. CONCLUSION

Issues relating to how vision links up with action in Nature's unmanned aerial vehicles such as insects and birds are really worth being investigated further. Houseflies are perfectly willing and able to show us at a moment's notice exactly what they are able to do. If we have not yet mastered their sophisticated skills, the fact that they can put on such good performances in spite of the low resolution of their eyesight at least shows that the solutions to the underlying problems must exist. These solutions rest on the one hand on specific behavioural strategies that reduce the computational burden, and on the other hand, on dedicated circuits based on exceptionally efficient signal processing architectures.

It was by first exploring the logic behind some specific neural network in the fly's compound eye, using microelectrodes and a specially designed

microscope, that we acquired the requisite basic know-how to be able to work on the lines which eventually yielded the robot prototype. This multidisciplinary project obliged us to blend lessons from animal vision, neurobiology, neuroethology, electronics, optics, control theory, information science and robotics.

In the general context of visually-guided navigation of natural or artificial agents, several points are worth mentioning:

1) With just a few pixels, it is possible to obtain skilled visually guided performances. Small numbers of pixels obviously mean considerable savings for designing future robots' eyes with parallel processing. The anthropomorphic notion that the visual guidance of an artificial agent must necessarily start with a pair of high resolution camera eyes needs to be re-considered: at least eighty percent of all the animal species do not do it this way.

2) The plain design of the camera eye with which vertebrates, arachnids and cephalopods are equipped, with its inherently limited field of view, does not necessarily give the right vista when designing robot's eyes. Drawing inspiration from the seven different types of arthropod compound eyes (57) may be a better approach. A compound eye in which each pixel has its own lens turns out to provide an efficient means of designing a panoramic visual field, and lends itself more readily to shaping a resolution gradient and a spatial filtering gradient. The interrelationship which exists in compound eyes between spatial sampling and contrast transfer was worked out long ago (37,65).

3) There exist some basic common constraints between the design of a seeing machine and that of a locomoting machine. Constructing a powerful robot by sub-contracting the visual system to one laboratory and the control system to another can therefore lead to a fiasco. Our project brought to the fore the tight interrelationship existing between vision and action (cf. 59). In both our robot and the fly, vision requires locomotion just as much as locomotion is guided by vision.

4) 'Motion blur' does not always constitute a plague in vision and can be put to good use by both natural and artificial creatures, provided their visual systems are equipped with a network of *motion sensors*. The idea that motion blur is detrimental to vision seems to have several origins. On the one hand, it stems from the misconception that an animal's retina may be like a photographic plate or CCD chip, the pixels of which respond to a *number* of absorbed photons (whereas animal photoreceptors respond, as we know, to a *rate* of absorbed photons). On the other hand it stems from the second misconception that animal's and human's visually-guided actions (including navigation) necessarily require a *static image* analysis process and hence are

based on a series of stable pictures, each of which is acquired during a given 'exposure time'. If the absence of motion during a 'frame' is required with most man-made optronic devices, this is due to the odd, *sequential* procedure used to read the electrical image - as opposed to the *parallel* reading of the electrical image which takes place in animal focal plane mosaics.

5) Motion detection plays a vital role in animal vision. It serves not only to find preys and mates and to escape predators. Most importantly, it helps animals to perceive their own ongoing bodily movements. This point seems to be still greatly underestimated in general, although several particularly perspicacious authors such as von Helmholtz, Exner and Gibson stressed it a long time ago (cf. 72).

6) Perceiving the optic flow requires a set of N motion detecting neurones, which process the information flowing onto the retina. The fly's visual system, like that of human beings, contains thousands of motion detecting neurones, each of which carries out a non-trivial task. Computers of the von Neumann type seem to be ill-suited to handling such a large body of data on line, especially when the agent is moving at a high speed. Moreover, digital computers can introduce undesirable effects due to the noncontinuity of the signals (amplitude discretization and temporal sampling), which in some cases can adversely affect the motion detection process.

7) The *parallel and analog* mode of processing - that with which animals' sensory systems operate - makes for fast sensorimotor computing. It can work efficiently even when the components are slow, inaccurate, and unmatched. It is likely that this kind of processing will be adopted in tomorrow's vehicles and microvehicles, using low-power analog VLSI circuits, with which massively interconnected, nonlinear processing circuits can be built efficiently and economically (51,18,55,21). Thus far, only few and elementary visuomotor systems have been produced on these lines, however (e.g. 20,17).

8) Accuracy is not at a premium when dealing with signal processing in sensory-motor systems. The problems are quite different in fact from those arising in the fields of mathematical computation and telecommunications. In the latter case, sounds or images have to be accurately transmitted or stored to be properly decoded by the fancy human receivers (ears or eyes).

The bionics approach we have adopted yields some valid solutions to the *low-level* visuomotor problem of obstacle avoidance in an uncertain, stationary environment. This problem has in fact been solved by animals throughout the course of evolution, and we have shown how the solution provided by insects can in fact be scaled up to a 10 Kg robot. The animals' own solutions are

necessarily both feasible and robust: they have withstood the test of time. Although most roboticists today do not care what solutions may be adopted by animals, they might have much to learn from Nature's ingenious tricks about how to process sensory-motor signals with minimal power, size, time and cost. This is particularly telling in the field of microrobotics (33) where the development of *microvehicles* destined for applications of various kinds depends on the possibility of overcoming the dramatic lack of decent one-cubic-millimeter visual systems. The emergence of flying microvehicles (64,46) and the need to find means of controlling their dynamic stability and visually-guided navigation may well force von Neumann architectures to the wall. Animals are sighted and locomoting agents which not only provide us with eloquent proof that there exist physical solutions to elusive problems such as those involved in visually guided navigation: they also provide us with guidelines for producing efficient robots which are akin to biological systems in spirit. Pursuing investigations on this topic is a really worthwhile scientific challenge, since it seems to work both ways at once, furthering the cause of both neuroscience and robotics.

The market for autonomous mobile vehicles endowed with visual capacities hardly exists yet, but there will be great potential for visually-guided terrestrial, airborne, underwater and space vehicles of all kinds in the centuries to come. It is time for us to realize that even the 'automobiles' of which we have been so proud, from Cugnot's steam car (1770) to the Rolls Royce, are simply blind. These perfidious creatures, as we know, have always cheated by relying completely on the visuomotor skill of a biological operator.

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