EXPERIMENTS WITH SIX-LEGGED WALKING MACHINES WITH FIXED GAIT

U. Mocci, M. Petternella, and S. Salinari

Summary

The traditional means of locomotion using rolling supports for displacement are inadequate for motion over rough terrain. Several solutions have been proposed for this problem in the technical literature. Machines using articulated supports similar to those of animals have been studied and designed.

In this paper some problems and relative solutions used in a new experimental vehicle (ESA UNO) are presented. This machine has six supports, and each support is formed by two segments. The upper one is linked to the main body by a cilindrical hinge while the lower is linked to the upper by a slider.

The motion of the proposed machine follows rectilinear trajectories, without other components of velocity that are in the direction of motion. To make this possible it is required that only the value of displacement velocity is imposed. The control system allows the motion over level or sloping, smooth or rough terrain.

The gait adopted is characterized by alternate motion of the tripod gathered supporting legs.

Introduction

Over the past two years, increasing interest has been shown in vechile capable of moving over unprepared or slippery terrain. Under such conditions, the performance of conventional wheeled vechiles is inadequate. Tracked or air-cushion vechiles also have limitations, mainly because the supporting medium is constrained to follow the gross profile of the terrain at all the times. Moreover the latter type of vehicle cannot negotiate excessively uneven ground and also needs an atmosphere to work in.

In principle, the best solution is that in which the supports touch a small and suitably selective area of ground. This can be obtained by using supports made up of appropriately controlled arrangements of levers similar to the legs of living organisms. The task of the driver of such a vechile should be similar to the task of the driver of a conventional vechile, who basically controls only the overall motion and decides its parameters such as direction and speed. An excessive effort required of the driver of a new type of vechile would slow down or even prevent its use. Hence, multi-legged vechiles of the type mentioned above require an automatic control system for maintaining balance and adapting the sup-

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ports to the condition of the ground where contact takes place, and for the execution of the succession of motion phases by the various segments which make up the legs.

In solving these problems, in current research being done at the Centro di Studio dei Sistemi di Controllo e Cacolo Automatici C.N.R. and at the Instituto di Automatica dell'Universita di Roma, it appeared best to consider vehicles with six supports. In this case, control problems are simplified.

In what follows, the control system structure will be illustrated, together with the solutions adopted for the various operating conditions.

General Description

Analysis of movement of a vehicle with articulated supports shows that, if its performance is to be adequate, it must be able to execute a number of different gaits with different parameter values (such as pace-length). The choice of gait and other parameters must be carried out automatically in accordance with the motion and the average condition of the terrain. Moreover, since the incorrect motion of one support (due, for instance, to disturbances) affects the motion of all the others and the attitude of the vehicle, it is necessary to adapt the motion of each support to the ground. This reduces the effects of disturbances due to the interaction of the supports through the body of the vehicle itself.

A possible way of organizing a vehicle control system satisfying the above conditions is given in /1/. The structure is divided into five levels, each of which is concerned with one aspect of the process of locomotion:

- the first level comprises the mechanical structure and the servomechanisms and establishes interaction between the latter so as to make the motion of the supports as smooth as possible;
- the second level generates the laws of motion, taking into account the necessary local adaptation of each support to the ground;
- the third level coordinates the chosen gait and determines, for each support, the instances in which it passes from the sustaining to the swinging phase and vice-versa; and for all the supports it determines the sequences for chan-

ging from one gait to another;

- the fourth level has the task of choosing the appropriate gait, taking into account the stability of the vehicle and energy characteristics of the motion;
- lastly the fifth level corresponds to the decisions of the driver, who supplies the vehicle with information concerning the overall motion parameters such as speed and direction.

The control strucure also includes the measuring system which transmits the necessary information to each level.

In order to weigh up the possibility of implementing a control system of the type described it was decided to investigate simplified models. This procedure allows evaluation, as regards the various aspects of control, of the validity of those solutions that can be extended to more complete vehicles.

The first model tried out, named ESA-UNO, which will be referred to in what follows, has the control system which is an implementation of the first two control system levels and of that part of the third level which is concerned with gait coordination. It is a vehicle with fixed gait and pre-set parametrs, able to move over various level or sloping terrains at constant speed. Moreover, solution of the problem of changing direction was not undertaken in this first model. Hence, it can move only along a straight line.

The mechanical structure used is technologically very simple, but does permit us to check whether the control system is able to allow motion to take place according to the established specifications. The vehicle has a rigid structure and there is no elastic suspension system. Hence the task of reducing the disturbances due to motion over uneven terrain is left entirely to the control system. The six supports are fitted to the ends and middle of the rectangular platform (Fig. 1a). Their structure stems from the way the control takes place. In this particular case the upper segment of the supports is connected to the platform by an axial hinge and to the lower segment by a stright sliding mechanism (Fig. 1b).

Tripodic gait was chosen /2/, in which three supports (the end ones on one side and the middle one on the other) are always touching the ground. This gait has a number of advantages: it enables static equilibrium to be maintained during motion while allowing the speed to be varied within fairly wide limits, and theoretically it requires only a relatively simple control system since it is made up of only two distinct phases.

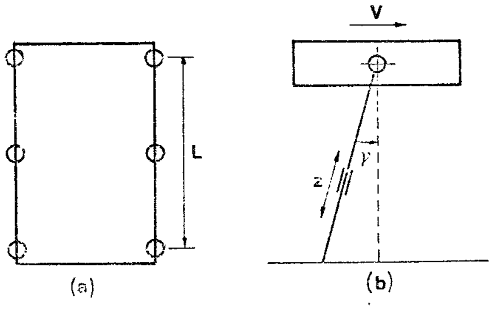


Fig. 1.

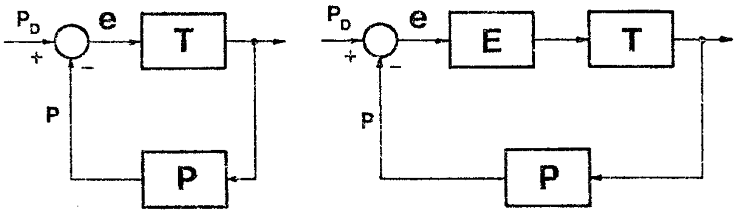
The First Control Level

The first level of the system comprises, as well as the mechanical structure described above, the servomechanisms which control the motion of each support according to the trajectories determined at the second level. Owing to the gait chosen, the three supports belonging to the same tripod move together; thus in the ideal case it would be possible to apply identical inputs to the servomechanisms of both the sustaining tripod supports and the swinging tripod supports. In reality this is possible only for the swinging supports, since if the vehicle is moving over rough and/or sloping ground the servomechanism inputs in general have to be different if the vehicle is to move correctly. This will be seen in greater detail in what follows.

Consequently, the set of servomechanisms can be represented as shown in Figure 2a, where:

$p_D^T = (\gamma_{1Ds}, \gamma_{2Ds}, \gamma_{3Ds}, z_{1Ds}, z_{2Ds}, z_{3Ds}, \gamma_{1Dp}, \gamma_{2Dp}, \gamma_{3Dp}, z_{1Dp}, z_{2Dp}, z_{3Dp})$

is the input vector whose components are the instantaneous required values of the angles γ and the extensions z for the sustaining tripod $/\ /_s$ and the swinging tripod $/\ /_p$. It should be noted that certain indicated values can be identical.



(a) Fig. 2. (b)

The vector:

$$p^T = (\gamma_{1s},\gamma_{2s},\gamma_{3s},z_{1s},z_{2s},z_{3s},\gamma_{1p},\gamma_{2p},\gamma_{3p},z_{1p},z_{2p},z_{3p})$$

is the vector of real angles and extensions; and

$$e^T = (\gamma_{1Ds}-\gamma_{1s},\ldots z_{1Ds}-z_{1s},\ldots \gamma_{1Dp}-\gamma_{1p},\ldots z_{1Dp}-z_{1p},\ldots)$$

is the error vector.

P is the diagonal matrix of position transducers which measure the position of each support relative to the platform, and the positions of the two segments of each support relative to each other.

T is the matrix which represents the control organs and the actuator. Since the various servomechanisms network were synthesized by considering a simplified non-interacting model, matrix T is also diagonal.

Actually interaction does take place between the supports through the mechanical structure, so that incorrect motion of one support (due, for instance, to an unevenly distributed load) has an effect on the motion of whole vehicle.

A solution to this problem has been put forward in / 3/.The block diagram in Figure 2a is modified as in Figure 2b by adding a particular error processing matrix E. Through this matrix the output of each servomechanism is affected not only by its own error but also by the other equivalent errors belonging to the same tripod.

In the particular case in which identical inputs are applied to the servomechanisms ($\gamma_{1DS}=\gamma_{2DS}=\gamma_{3DS}, z_{1DS}=z_{2DS}\ldots$) the matrix E takes the following particularly simple form:

$$E = \begin{bmatrix} E_0 & & & 0 \\ & E_0 & & \\ & & E_0 & \\ 0 & & & E_0 \end{bmatrix}, \qquad E_0 = \begin{bmatrix} 1 & -K & -K \\ -K & 1 & -K \\ -K & -K & 1 \end{bmatrix}$$

As can be seen, the servomechanism inputs are the differences between their respective error signals and the sum, weighted by an interaction coefficient K, of the errors of the other two supports of the same tripod. This correction is independent for γ and for z. This structure allows interaction to take place between the supports of the same tripod in such a way as to reduce the position differences due to torque or parameter variation disturbances acting differently on each support; moreover the whole vehicle stops automatically if one support is stopped.

If the servomechanism input signals differ, then the interaction which ought to take place in order to maintain all the above properties is dynamic and, hence, more complex. However, use of the above instantaneous interconnection matrix does not alter the equal distribution of disturbances, while system response in regard to other requirements is not worsened. Hence, the above interconnection is maintained under all conditions, even if it is less useful when the inputs differ.

The Second Control Level

The second level of the control system has the task of generating the laws of motion to be applied to the servomechanism inputs during the sustaining and swinging phases of the supports. The times at which these trajectories are applied to their respective servomechanisms are determined by the gait coordination organ.

It should be kept in mind that the laws of motion used during the sustaining phase must enable the vehicle to move according to the required specifications over level or sloping, smooth or rough ground. To this end, basic trajectories for motion over level or sloping smooth ground were found. Suitable variation of certain parameters of these trajectories allows adaptation of the motion to rough ground. Therefore, two subphases can be distinguished in the generation of the sustaining phase laws of motion: in the first one the parameters of the laws of motion are calculated, in the second the trajectories are actually generated.

If motion takes place over smooth terrain the parameter variations of the laws of motion are mainly due to the slope of ground. The gradient β is computed with reference to the pair of sustaining supports on the same side of the platform, according to the following equations (Fig. 3):

$$tg\beta = \frac{H_{2in} - H_{1in}}{D} \qquad (1)$$

where H_{1in} and H_{2in} can easily be found at the instant in which the supports touch the ground from the measured values of γ_{in} and z_{in}:

$$\begin{aligned} H_{1in} &= z_{1in} \cos \gamma_{1in} \\ H_{2in} &= z_{2in} \cos \gamma_{2in} \end{aligned} \qquad (2)$$

while D is given by the following expression:

$$D = L + z_{1in} \sin \gamma_{1in} - z_{2in} \sin \gamma_{2in} \qquad (3)$$

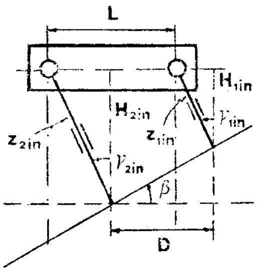


Fig. 3.

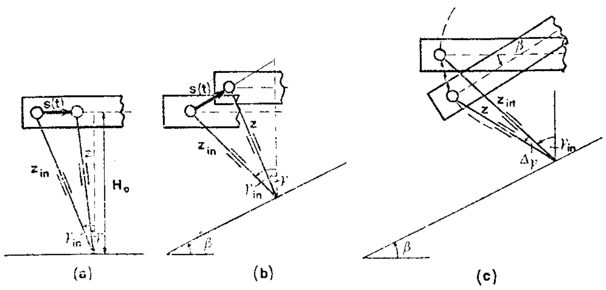


Fig. 4.

The analytical expression of the laws of motion over level ground was obtained by constraining the vehicle to maintain horizontal attitude while moving /4/. The trajectories of the two segments can be obtained from Figure 4a, letting:

$$s_{in} = z_{in} \sin \gamma_{in} \qquad (4)$$

It follows that:

$$\begin{aligned} \gamma(t) &= \operatorname{artg} \frac{s_{in} - s(t)}{H_o} \\ z(t) &= \frac{H_o}{\cos\left(\gamma(t)\right)} \end{aligned} \qquad (5)$$

where s(t) is the displacement of the platform in the direction of motion, whose instantaneous value is fixed by the pilot. If movement takes place over ground with a given slope, two cases can be distinguished. According to whether the evaluated slope is less or greater than a certain value, it is better to keep the vehicle horizontal or set it parallel to the ground. In the former case, the laws of motion which must be generated, with reference to Figure 4b, have the following expression:

$$\gamma(t) = \frac{s_{in} - s(t)\cos\beta}{s(t)\sin\beta - H_{in}}$$

$$z(t) = z_{in}\frac{\cos(\gamma_{in} - \beta)}{\cos\{\gamma(t) - \beta\}} \qquad (6)$$

It is obvious that Expressions 5 can be considered a particalr case of Expressions 6 for $\beta=0$.

If the vehicle is to be set parallel to the ground, different laws of motion must hold, since in this case the vehicle rotates through an angle equal to β about an axis passing through the two central support hinges (Fig. 4c). Accordingly, the other supports must undergo a positive or negative variation $\Delta\gamma$ whose value is:

$$\Delta\gamma = \text{artg}\frac{\frac{L}{2}\sin\frac{\beta}{2}\ (\sin\gamma_{in} - \cos\gamma_{in})}{z_{in}^2 - \frac{L}{2}\sin\frac{\beta}{2}\ (\sin\gamma_{in} - \cos\gamma_{in})} \qquad (7)$$

and a variation ΔZ, whose value is:

$$\Delta z = z_{in} - \frac{L}{2}\,\frac{\sin\beta}{\sin\Delta\gamma}\sin(\gamma_{in} - \frac{\beta}{2}) \qquad (8)$$

Letting:

$$s'_{in} = (z_{in} + \Delta z)\sin(\gamma_{in} + \Delta\gamma)$$

$$\Delta H = \Delta z\cos(\gamma_{in} + \Delta\gamma) \qquad (9)$$

the laws of motion of the outer supports are now:

$$\gamma(t) = \text{artg}\frac{s'_{in} - s(t)}{H + \Delta H}$$

$$z(t) = \frac{H + \Delta H}{\cos\gamma(t)} \qquad (10)$$

The central support motion laws, on the other hand, do not change with respect to when motion takes place over level ground. It should also be noted that to avoid sharp variations of the servomechanism reference signals, the variations ΔH and $(s_{in} - s'_{in})$ should be applied gradually during a complete pace-period.

If motion takes place over rough terrain the first problem to be faced is again how to determine whether the vehicle is or not on sloping ground and if so how to measure the slope. In any case it is best to average the measured values over a certain number of steps so as to reduce the error on the slope β due to stones or holes. The number of steps required is closely linked to the manner the state of the ground (sloping or level) is determined and will be discussed in the following paragraph.

Since the slope evaluated in this fashion is taken as being identical in the laws of motion of all the supports in the sustaining phase, in order to adapt the motion of the supports to the local terrain conditions, for each support touching the ground the value of H is taken as the actual height of its upper joint.

It is of interest to note that the same procedure can also be applied if the vehicle is moving up a slope diagonally. In this case the slope can be taken as that defined by the two outer supports, while the motion of the third one is adapted to the others.

Figure 5 is a general diagram of the various sustaining phase described so far.

During the swinging phase, the leg, which has reached its most backward position during the sustaining phase, is raised, moved forward and prepared for the next step. This phase can be executed in different ways. IT seems best to break it up into elementary movements, so that although it takes place slowly, the risk of the legs hitting the ground is minimized. Thus, the leg is first completely contracted, then swing forward (Fig. 6a), then extended until it reaches the next point of contact. Three possible methods for executing the last movement were examined. They are shown in Figure 6c, 6d and 6e. The support can be swung forward as far as necessary, and then extended until it touches the ground. Thus the angle γ_{in} remains constant even if the ground is uneven. Otherwise, it can be swung forward, partly extended, and then swung back until it touches the ground. In this case the the extension z_{in} remains constant even if the ground is uneven. Lastly, it can be swung forward until its end is vertical above the theoretical new point of contact, and then lowered until the end touches the ground. The new point of contact is found by keeping the step-length p constant. Thus both γ_{in} and Z_{in} vary if the ground is uneven. These different methods of execution were compared on the basis of the following factors:

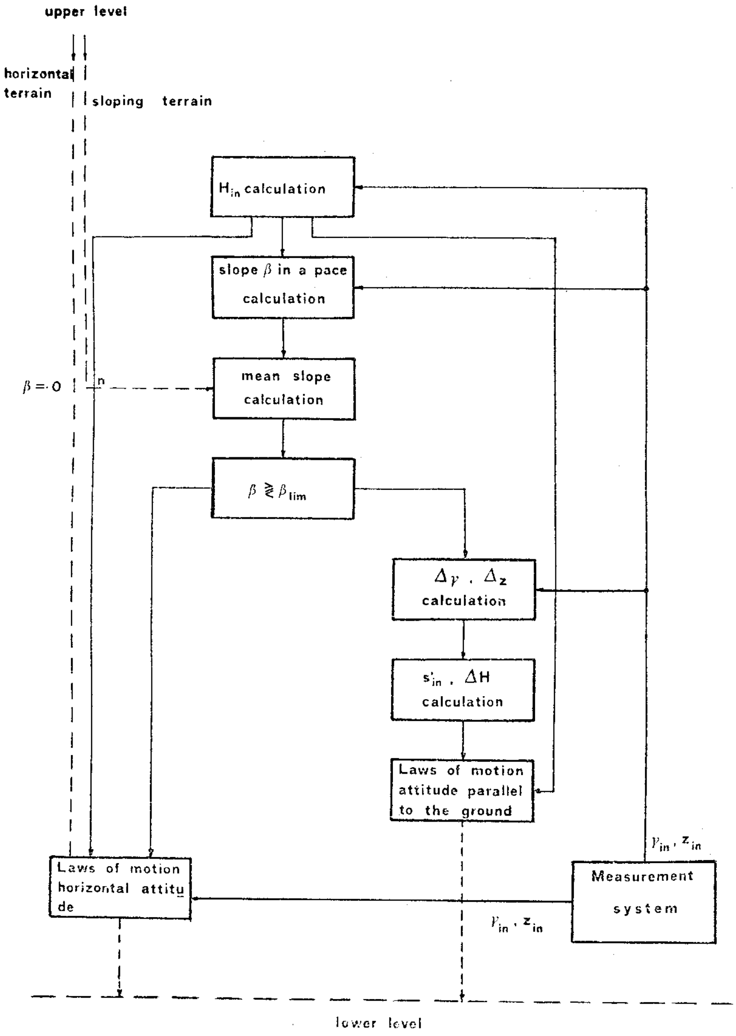

upper level
horizontal terrain
sloping terrain
H_{in} calculation
slope β in a pace calculation
$\beta = 0$
n
mean slope calculation
$\beta \gtreqless \beta_{lim}$
$\Delta\gamma$. Δ_z calculation
s'_{in} , ΔH calculation
Laws of motion attitude parallel to the ground
γ_{in} , z_{in}
Measurement system
Laws of motion horizontal attitude
γ_{in} , z_{in}
lower level

Fig. 5.

a) ease of implementation of the swinging phase laws of motion;
b) ease of parameter calculation for the sustaining phase which follows;
c) speed with which the support strikes the ground.

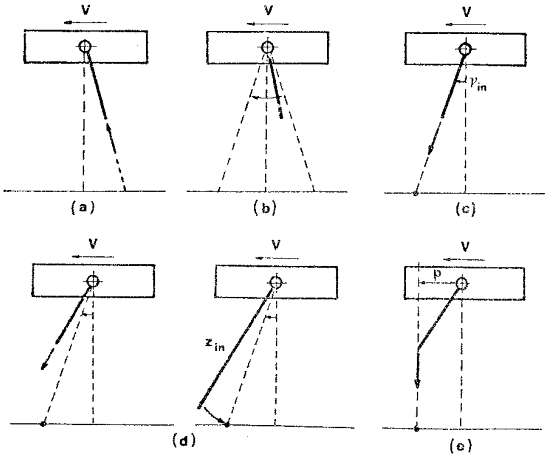


Fig. 6.

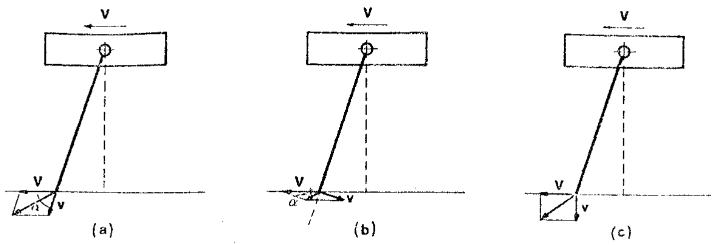
For this purpose, Table 1 gives the motion law expressions for the last part of the swinging phase, the expression for the slope, the sustaining phase motion laws for horizontal vehicle attitude, the expressions for $\Delta\gamma$ and ΔZ for motion over sloping terrain with the platform parallel to the ground, and the absolute value of the velocity with which the support strikes the ground. The last of these calculations for the three cases was carried out under the hypothesis shown in Firgure 7a, b, and c respectively. The table shows that the motion laws for the last part of the swinging phase are simpler for γ_{in} = const. or Z_{in} = = const. than for p = const. On the other hand the evaluation of the slope and the implementation of the sustaining phase motion laws with horizontal platform attitude are easier for γ_{in}=const. or p = const. than for Z_{in} = const.

The increments $\Delta\gamma$ and ΔZ for motion over sloping terrain with the platform parallel to the ground are calculated most easily for γ_{in} = const., and least easily for Z_{in} = const. Lastly, the smallest impact velocity is obtained for Z_{in} = const.

Table 1.

	LAWS OF MOTION SWINGING PHASE		CALCULATION OF SLOPE	LAWS OF MOTION SUSTAINING PHASE (HORIZONTAL ATTITUDE)		CALCULATION OF $\Delta\gamma$, Δz (ATTITUDE PARALLEL TO THE TERRAIN)		IMPACT VELOCITY
	γ	z	$tg\beta$	$tg\gamma$	z	$\Delta\gamma$	Δz	
$\gamma_{in}=\text{const}$	$\gamma=\gamma_0$	$z=z_{ref}$	$\frac{\cos\gamma_0(z_{2in}-z_{1in})}{L-\sin\gamma_0(z_{2in}-z_{1in})}$	$\frac{z_{in}\sin\gamma_0-s(t)\cos\beta}{s(t)\sin\beta+z_{in}\cos\gamma_0}$	$z_{in}\frac{\cos(\gamma_0-\beta)}{\cos(\gamma-\beta)}$	$\text{arctg}\frac{\frac{L}{2}\sin\beta(\sin\gamma_0-\cos\gamma_0)}{z_{in}^2-\frac{L}{2}\sin\beta(\sin\gamma_0-\cos\gamma_0)}$	$z_{in}-\frac{\frac{L}{2}\sin\beta}{\sin\Delta\gamma}\sin\left(\gamma_0-\frac{\beta}{2}\right)$	$\sqrt{V^2+v^2+2vV\sin\alpha}$
$z_{in}=\text{const}$	$\gamma=\gamma_{ref}$	$z=z_0$	$\frac{z_0(\cos\gamma_{2in}-\cos\gamma_{1in})}{L-z_0(\sin\gamma_{2in}-\sin\gamma_{1in})}$	$\frac{z_0\sin\gamma_{in}-s(t)\cos\beta}{s(t)\sin\beta+z_0\cos\gamma_{in}}$	$z_0\frac{\cos(\gamma_{in}-\beta)}{\cos(\gamma-\beta)}$	$\text{arctg}\frac{\frac{L}{2}\sin\beta(\sin\gamma_{in}-\cos\gamma_{in})}{z_0^2-\frac{L}{2}\sin\beta(\sin\gamma_{in}-\cos\gamma_{in})}$	$z_0-\frac{\frac{L}{2}\sin\beta}{\sin\Delta\gamma}\sin\left(\gamma_{in}-\frac{\beta}{2}\right)$	$\sqrt{V^2+v^2-2Vv\sin\alpha}$
$p=\text{const}$	$\gamma=\gamma_{ref}$	$z=\frac{p}{\cos\gamma}$	$\frac{p(\text{cotg}\,\gamma_{2in}-\text{cotg}\,\gamma_{1in})}{L}$	$\frac{p-s(t)\cos\beta}{s(t)\sin\beta+H_{in}}$	$z_{in}\frac{\cos(\gamma_{in}-\beta)}{\cos(\gamma-\beta)}$	$\text{arctg}\frac{\frac{L}{2}\sin\beta(p-H_{in})}{z_{in}^2-\frac{L}{2}\sin\beta(p-H_{in})}$	$z_{in}-\frac{\frac{L}{2}\sin\beta}{\sin\Delta\gamma}\sin\left(\gamma_{in}-\frac{\beta}{2}\right)$	$\sqrt{V^2+v^2}$

In conclusion, it is remarked that the final choice of laws of motion for a true moving vehicle also depends on the form chosen for the lower end of the leg, which in practice must have a suitable area of contact.



(a) (b) (c)

Fig. 7.

The Third Control Level

The motion coordination of a vehicle described above is fairly simple, since its gait is fixed and has constant parameters. The principal tasks carried out at this level are slope evaluation, gait coordination, and coordination of the various parts which make up the sustaining and swinging phases. Concerning slope evaluation, it can be noted that for motion over level ground the average of the heights of the upper joints of each leg must be approximately equal over a sufficient number of steps. That is, letting $H_{i(j)}$ be the hight of the j-th leg during the i-th step, the following expression must hold:

$$\frac{\sum_{i=1}^{n} H_{i(1)}}{n} \simeq \frac{\sum_{i=1}^{n} H_{i(2)}}{n} \simeq \frac{\sum_{i=1}^{n} H_{i(3)}}{n} \qquad (11)$$

Expression 11 does not hold for motion over sloping ground. The number of steps n over which the average is taken is a compromise between the need to satisfy Expression 11 when the ground is level and the need to sense promptly terrain sloping. This value can be fixed by the driver. In practice for ground which seems horizontal or has small changes of slope, n can be made large and the state of the ground evaluated through Expression 11, since a delay in the recognition of the slope would not greatly endanger the motion of the vehicle. On the other hand if the driver sees sharp changes of slope, then he must suitably reduce n so that the vehicle's motion can adapt more rapidly to the state of the ground. Naturally, it is also convenient to use the same value of n for evaluating the slope β by averaging the values found over a number of steps using Expression 1.

The other task carried out at this level is, as already mentioned, coordination of the sustaining and swinging phases. During the latter phase, information concerning the positions of the supports with respect to one another and to the platform allows determination of the instants at which one subphase gives way to the next. Contact of the support with the ground determines the instant in which swinging ends and sustaining begins. If, because of uneven ground, the support makes contact before having completed the swinging phase, it must nonetheless switch to sustaining.

There are a number of details to be borne in mind concerning sustaining phase coordination. In the ideal case the sustaining phase corresponds to the time interval in which only one tripod is touching the ground. Therefore, the changeover from one tripod to another should take place instantaneously. In practice this is not so, since for obvious reasons of safety the two tripod sustaining phases are made to overlap even for motion over smooth ground. Moreover, when motion takes place over irregular terrain the three supports of a tripod will usually touch ground at different times. From the above remarks it follows that there will be time intervals in which more than three supports are touching the ground, and the instants of contact will differ from one support to another. In this case the motion law parameter calculation for each support entering the sustaining phase is done by evaluating Y_{in}, Z_{in} and H_{in} for such support as soon as it touches the ground so that its motion adapts immediately to that of the tripod which was sustaining before. For motion on a slope the same gradient as for the supports which were previously sustaining is adopted. This value is updated when all three supports of the new tripod are touching the ground.

It should also be noted that, owing to the essentially rigid mechanical structure used, when more than three supports are sustaining not all of them effectively touch the ground during motion. However the laws of motion applied to the servomechanisms must always be those of the sustaining phase.

For motion on a slope with the platform parallel to the ground it is also necessary, in order to maintain the same vehicle balance conditions, to suitably vary the angle through which the supports move. A vertical sensor fitted to the platform would, under these conditions, allow a useful comparison to be made between the measured and calculated slopes. Such a sensor would also be useful for motion on a slope with horizontal platform for detecting any attitude errors which could falsify the calculated slope value.

The ESA-UNO Experimental Vehicle

The solutions put forward above are being tried out using an experimental machine named ESA-UNO* (Fig. 8). This vehicle, as already stated, has two degrees of freedom per support and thus can move over varied terrain in one direction only. The mechanical structure and servomechanisms, which make up the first level, can be considered separately from all the other control levels. This is because the mechanical structure and power devices were used to evaluate the performance of the control system implemented either with adhoc designed hybrid devices, or programming a small process computer with suitable interface.

In reality, the limited performance required of ESA-UNO can be obtained with a relatively simple analog control unit, the reliability, flexibility and economy of which are matched with that of a small digital computer. For instance, motion over level rough

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*The following people participated in the construction of the experimental vehicle used to confirm the choice illustrated in this paper: S. Baldini, C. Caruso, F. Di Giacinto, G. Federico, S. Medici.

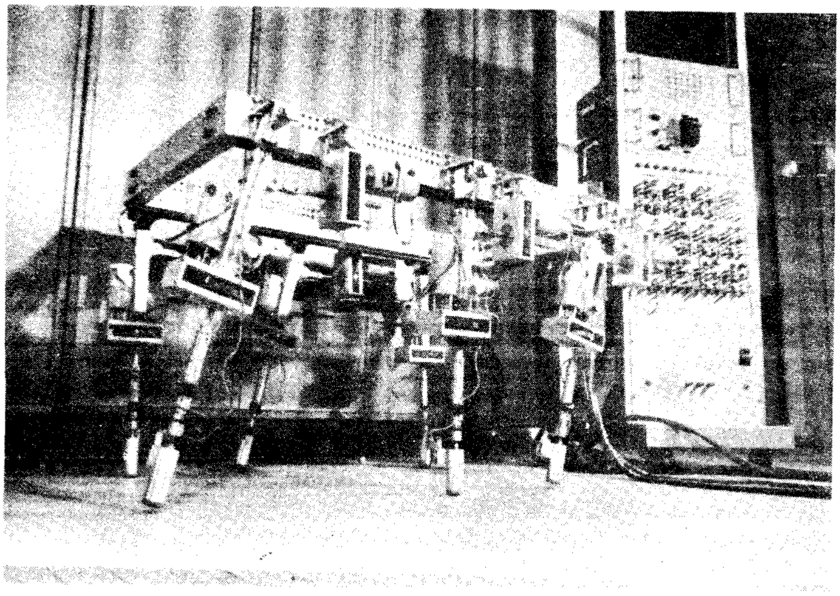
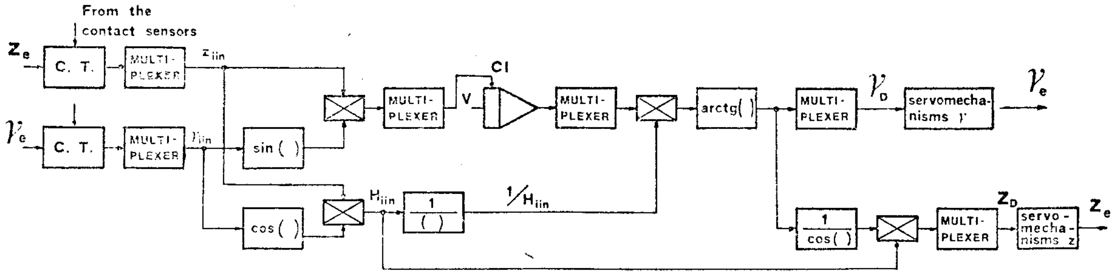


Fig. 8.

terrain can be obtained with the control circuit shown in Figure 9. This circuit can be easely built since the arguments of the trigonometric functions to be relized are restricted for this application, and thus can be piecewise lineraly approximated with only a few segments.

Moreover, it should be borne in mind that, since the sample and hold circuits CT have at their output for the whole step duration the initial angles and extensions measured separately for each leg, a suitable multiplexer control allows a single organ to calculate the laws of motion for each support independently. Thus the control system can be adapted to gaits other than alternate tripods. Since a vehicle suitable for moving over any type of ground and in any direction obviously requires a more complex control system, only experience can show whether it is best to resort to an entirely digital system or to a hybrid one in which the laws of motion are generated in analog fashion.



C. T.	sample and hold circuit
γ_D , z_D	reference input
γ_e , z_e	servomechanisms output
γ_{in} , z_{in}	values of γ and z at the contact instant
H_{in}	value of H " " " "
C I	initial conditions
V	speed value

Fig. 9.

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