Global Journal of Engineering and Technology [GJET].
ISSN: **2583-3359** (Online)
Frequency: Monthly
Published By GSAR Publishers
Journal Homepage Link- https://gsarpublishers.com/journal-gjet-home/

SYNCHRONIZATION IN THE SYNTHESIS OF WALKING MOBILE MECHANISMS

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Article History

Received: 15/10/2026
Accepted: 21/10/2026
Published: 27/10/2026

Vol – 5 Issue – 10

PP: - 19-24

Abstract

Synchronization is a type of characteristic of kinematic chains, which determines the capabilities of the kinematic chain to perform a certain number of technological processes. Synchronization has a probabilistic nature and is strongly influenced by redundancy. The publication presents a mathematical approach for the synthesis through synchronization of locomotion mechanisms, as the most representative synchronous technological process, composed of kinematic chains with a high degree of redundancy.

Keywords: *robot, synthesis, locomotion.*

1. INTRODUCTION

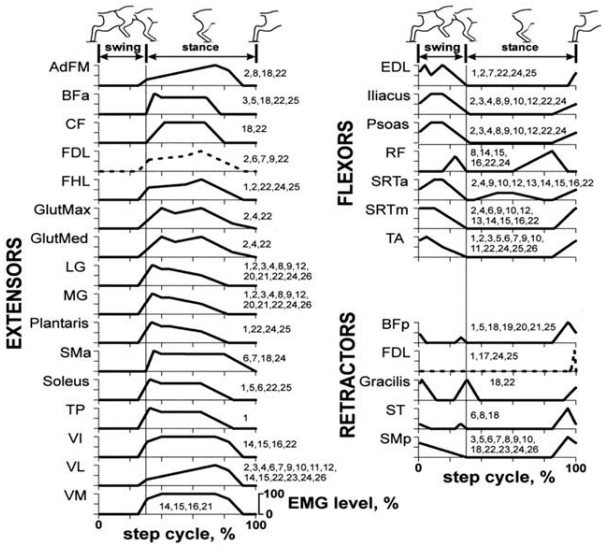
Each kinematic chain is synthesized to perform a certain set of technological sequences. The more degrees of freedom a kinematic chain has, the more technological possibilities it has, from a mechanical point of view. Moreover, the greater the redundancy of the kinematic system, the greater its technological possibilities.

Looking at the issue through the prism of Combinatorics, the options for technological possibilities grow exponentially with increasing redundancy. The vast majority of the options for technological possibilities follow certain sequences of movement of individual kinematic links, that is, a certain regular sequence or, in short, synchronization of kinematic links is noticeable.

Locomotion is one of the most characteristic technological processes, which is a combination of synchronized movements, but each individual section of the kinematic chain could also perform independent movements under certain conditions [1]. The dependence of movements in the locomotion of walking mechanisms is expressed by the synchronization of the drive of the individual degrees of freedom of the mobile robot. The synchronization of movements can be performed mechanically through dependent movements in the mechanisms, but it can also be set software-wise, by controlling individual independent actuators [2]. Synchronization plays a very important role in the synthesis of complex mechanisms. Synchronization makes it possible to systematize the variants of technological processes and possible variants of kinematic provision for their implementation. Moreover, through synchronization, work is assigned to individual actuators that are part of the complex - long kinematic chains of machines.

In living nature, synchronization is present throughout the Fauna. All living creatures use synchronization to realize their vital functions. . There are many diagrams that have been taken by biologists.

Fig. 1 and Fig. 2 show such diagrams of an animal and a person during locomotion.



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Fig. 1. Synchronization of the hind leg muscles of a quadruped animal during the two phases of the stride [3]

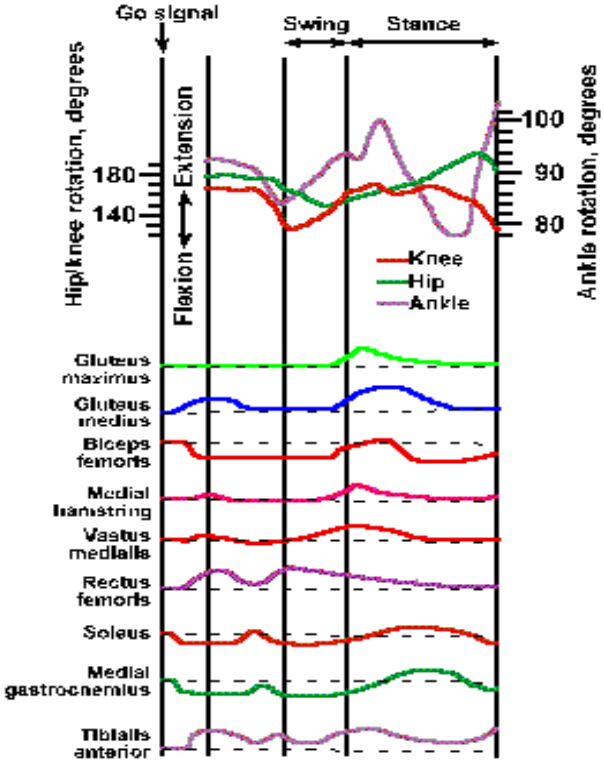


Fig. 2. Synchronization of the muscles of one leg of a person during the two phases of the stride [3].

The task of this publication is to show how synchronization can be used in the synthesis of kinematic chains with a high degree of redundancy.

2. EXPLANATION

Synchronization gives the relationship between the time t and the geometric quantities of the input and the reading of the movement of the mechanism at its output.

In the presence of synchronization between two or more mechanisms, one cannot speak of separate mechanisms, but of one whole, complex mechanism.

An important point is that it is not necessary for any connection to exist between the individual mechanisms, be it mechanical or electrical, it is enough for there to be an *unambiguous determination*. That is, the input signal to correspond unambiguously (linearly or nonlinearly) to the result of the output, in this case we are talking about synchronization regardless of how many individual mechanisms are involved or how long the kinematic chain is.

During locomotion, during the execution of the individual phases of a double step, the number of degrees of freedom of the walking mobile mechanism changes. This shows that there are situations in which the kinematic chain of the mobile robot has a high degree of redundancy (to a large extent, this circumstance is also influenced by the type of gait). In this case and in other similar cases, only synchronization would give the unambiguous determination of the movement of the mechanism.

Classification of synchronization can be made:

1. **According to the method of synchronization:**

– by branching;

– by converting the action from one type to another: through addition and subtraction.

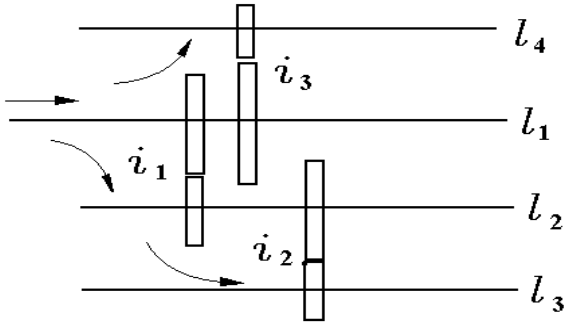


Fig. 3. Branching of the movement.

Fig. 3 the motion is transmitted along the path of the arrows. It starts from a shaft l_1 and through the gear pair with a gear ratio i_3 the motion is transmitted to shaft l_4 , thus branching into two motions with different rotational frequencies. Similarly, the branching is obtained through the gear ratio i_1 of shaft l_2 . Finally, through the gear ratio the motion is branched to shaft l_3 . In this way, the motion assigned to the first shaft is branched and *synchronously* drives the other shafts, through gear ratios (gear functions). This scheme is valid not only for gear mechanisms but also for all other mechanisms.

Motion transformation is another type of synchronization of motion:

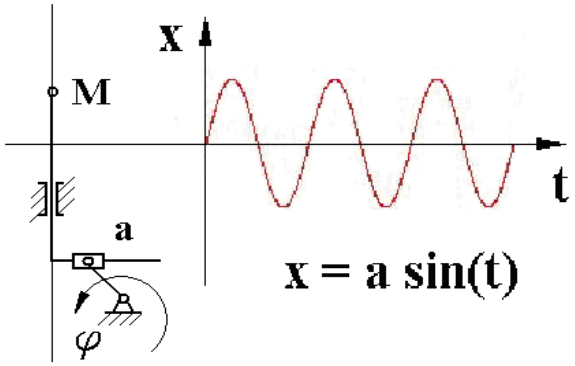


Fig. 4. Motion transformation.

When converting motion, a transition from one type of motion to another type of motion is achieved (Fig. 4 shows the conversion of motion from rotary to reciprocating), which is uniquely determined.

Addition and subtraction of motions is also a type of synchronization of motion. This is achieved with differential mechanisms [4…7] regardless of the basis on which they are built (gear, lever, etc.). In robotics, they are used mainly when

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the motors are moved away from the driven unit, resulting in the so-called coupling of motions and the need for subsequent decoupling of motions.

Regardless of how many degrees of freedom the differential mechanism has, the unambiguous determination of motion is present, since each degree contributes uniquely to the overall motion of the mechanism.

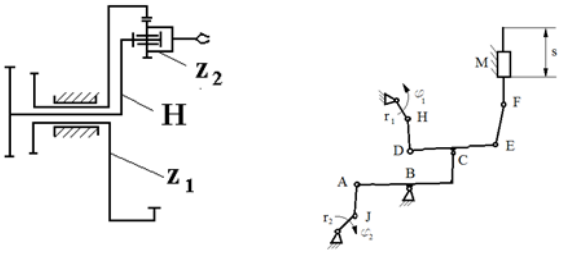


Fig. 5. Differential mechanisms [8,9].

The gear ratio is found using the Willis inversion method, i.e.:

(1.)

$$i_{12}^{H}=\frac{w_1^H}{w_2^H}=\frac{w_1-w_H}{w_2-w_H}=\pm\frac{z_2}{z_1}=\frac{r_2}{r_1}$$

from here the outgoing angular velocity can be expressed:

$$w_2=i_{21}^{H}w_1+w_H\left(1-i_{21}^{H}\right)=i_{21}^{H}w_1+i_{2H}^{1}w_H$$

where:

$i_{21}^{H}=\frac{1}{i_{21}^{H}}=\frac{z_1}{z_2}=\frac{r_1}{r_2};i_{2H}^{1}=1-i_{21}^{H}=1-\frac{z_1}{z_2}$. The sign "+" is for internal engagement, and "-" for external engagement.

Motion decoupling is used when the motors are not on one of the links of the kinematic pair and the motion must be transmitted through other kinematic pairs. In the general case for a manipulation system with "n" number of motors and actuators, the relationship between the angles of rotation of the motors $\vec{\psi}=\left(\psi_1,\psi_2,...,\psi_n\right)^T$ and the angles of rotation of the actuators $\vec{q}=\left(q_1,q_2,...,q_n\right)^T$ is given by the matrix of the specific transmission ratios T [10…13]:

(2)

$$\vec{\psi}=\begin{vmatrix}\psi_1\\ \psi_2\\ \vdots\\ \psi_n\end{vmatrix}=\begin{vmatrix}\frac{\partial\psi_1}{\partial q_1} & \frac{\partial\psi_1}{\partial q_2} & \cdots & \frac{\partial\psi_1}{\partial q_n}\\ \frac{\partial\psi_2}{\partial q_1} & \frac{\partial\psi_2}{\partial q_2} & \cdots & \frac{\partial\psi_2}{\partial q_n}\\ \cdots & \cdots & & \cdots\\ \frac{\partial\psi_n}{\partial q_1} & \frac{\partial\psi_n}{\partial q_2} & \cdots & \frac{\partial\psi_n}{\partial q_n}\end{vmatrix}\times\begin{vmatrix}q_1\\ q_2\\ \vdots\\ q_n\end{vmatrix}=T\vec{q}$$

A necessary and sufficient condition for guaranteeing the independence of the drive is that the matrix T contains members only on the main diagonal, and the remaining positions are for the dependent motions. Here, as in the above cases, the dependent and independent motions are uniquely defined. In this case, we have:

(3) $$\psi_i=\left(\frac{\partial\psi_i}{\partial q_i}\right)q_i \quad ;$$

i=1,2,3,…,n

The partial derivative $\frac{\partial\psi_2}{\partial q_1}$ is the transfer function of the mechanism between the motor and the actuator. In open kinematic chains, when the motors are at the base or remote from the actuator, the matrix T contains terms only above the main diagonal. In this case, the above dependence takes the form:

(4)

$$\psi_1=\left(\frac{\partial\psi_i}{\partial q_i}\right)q_i+\left(\frac{\partial\psi_i}{\partial q_{i+1}}\right)q_{i+1}+...+\left(\frac{\partial\psi_i}{\partial q_n}\right)q_n$$

This is a typical example of dependent motion, which means that the movement of the *i*-th link can be $\left(q_i\neq 0\right)$ obtained $\psi_i=0$ if $q_{i+1},q_{i+2},...,q_n$ they are different from zero or at least one of them, i.e. the movement of the *i*-th is obtained from the movement of the links with a higher number.

For a three-link kinematic structure, the matrix T would look like this:

(5.)

$$\vec{\psi_3}=\begin{vmatrix}\psi_1\\ \psi_2\\ \psi_3\end{vmatrix}=\begin{vmatrix}\frac{\partial\psi_1}{\partial q_1} & \frac{\partial\psi_1}{\partial q_2} & \frac{\partial\psi_1}{\partial q_3}\\ 0 & \frac{\partial\psi_2}{\partial q_2} & \frac{\partial\psi_2}{\partial q_3}\\ 0 & 0 & \frac{\partial\psi_3}{\partial q_3}\end{vmatrix}\times\begin{vmatrix}q_1\\ q_2\\ q_3\end{vmatrix}=T_3\vec{q_3}$$

from which for the individual kinematic chains we obtain:

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(6.)

$$\psi_1 = \left(\frac{\partial \psi_1}{\partial q_1}\right) q_1 + \left(\frac{\partial \psi_1}{\partial q_2}\right) q_2 + \left(\frac{\partial \psi_1}{\partial q_3}\right) q_3;$$
$$\psi_2 = \left(\frac{\partial \psi_2}{\partial q_2}\right) q_2 + \left(\frac{\partial \psi_2}{\partial q_3}\right) q_3;$$
$$\psi_3 = \left(\frac{\partial \psi_3}{\partial q_3}\right) q_3.$$

The gear ratios in the T matrix are an extremely convenient form of recording the synchronization of a kinematic chain. The additional conditions imposed on the gear ratios actually lead to finding independent movements for industrial robotics, for walking mechanisms and their synchronization all possible solutions are important.

- gear ratios can be set to zero - a condition for independence of movements;
- gear ratios can be set to a constant - a condition for linear synchronization;
- gear ratios can depend on a parameter (function) - a condition for nonlinear synchronization.

Synchronization can serve to reduce the degrees of freedom of mechanisms with two or more degrees of freedom during synthesis.

In the presence of independent degrees of freedom, the presence of synchronization in a given time interval turns them into dependent ones for this time interval.

Practically, software support is a type of program synchronization of the independent degrees of freedom of the mechanism as a whole. If the mechanism is designed to perform only one trajectory throughout its entire life, then this software is redundant and the connection between the independent degrees of freedom can be mechanical. In this case, a reduction of the degrees of freedom of the mechanism occurs, i.e. we are talking about a reduction of the degrees of freedom for the given kinematic structure.

In practice, the equations of the connections between the independent degrees of freedom give the additional conditions for the synthesis of a kinematic chain with redundancy.

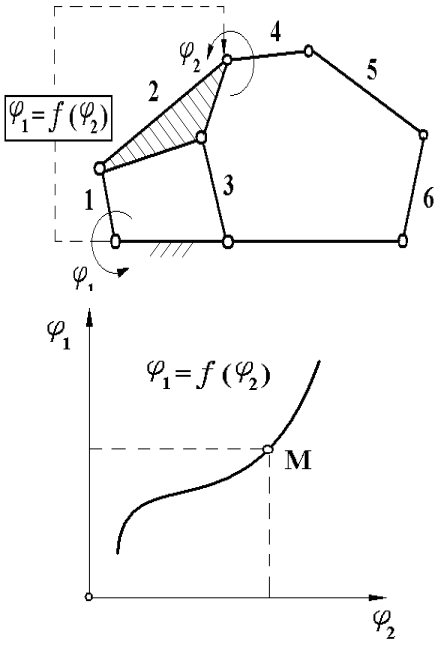


Fig. 6. Reduction of the degrees of freedom of a mechanism with two degrees of freedom due to synchronization

The function $\varphi_1 = f(\varphi_2)$ that connects the two degrees of freedom can be:

- linear, i.e. $\varphi_1 = k\varphi_2$, where: at $k = 0$, there is no synchronization, i.e. the function is parallel to the abscissa axis (respectively to the ordinate axis), at $k \neq 0$ there is a linear (proportional) dependence between the movements of the initial links;

nonlinear, i.e. $\varphi_1 = f(\varphi_2)$, in this case synchronization is present, but the connection between the initial links is a nonlinear function.

In a mechanism with three degrees of freedom, the dependence between the three initial links is a surface in space, in mechanisms with more degrees of freedom, unreal figures are obtained. For this reason, it is better to work with the parametric expression of these time dependencies.

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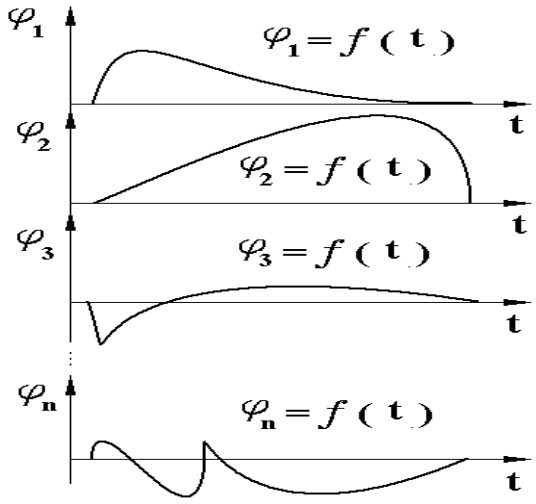


Fig. 7. Parametric view of the dependences of the movements of the initial links of a mechanism on one parameter

Synchronization can also be partial. With more degrees of freedom (more than 3), their reduction does not necessarily have to be reduced to one degree of freedom.

Another function of synchronization is in describing gaits. Locomotion is not free movement. The presence of a huge number of degrees of freedom, especially in kinematic structures in living nature, does not make the mechanism completely free. In order to realize a given gait, a harmonious and precise system of sequential cyclic movements of the motors (muscles in living nature) is necessary [14…18] on the basis of which synchronous movements are realized along the possible degrees of freedom.

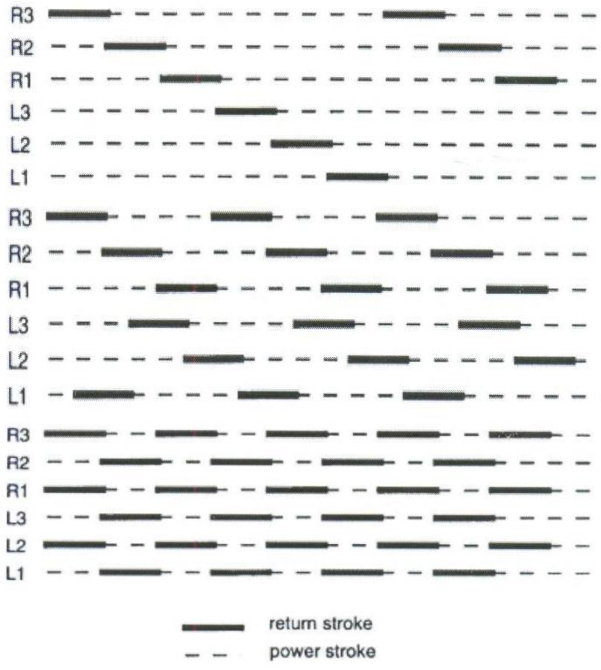


Fig. 8. Three types of gaits of a six-legged locomotion system [19] (hexapod or spider)

For the realization of a given gait, a given degree of freedom of the kinematic chain uses a small percentage of the capacity of the possible movement. If the gait is changed, then for this degree of freedom the possible capacity of the intended movement used will increase or decrease. Thus, the capabilities of the kinematic pairs impose a limit on the number of gaits used by a kinematic system.

Moreover, even after the invention of the camera for quick snapshots in 1877, it was seen that not only the extreme contact points, i.e. the feet, move along continuous periodic curves, but also the entire body moves along some continuous periodic curves.

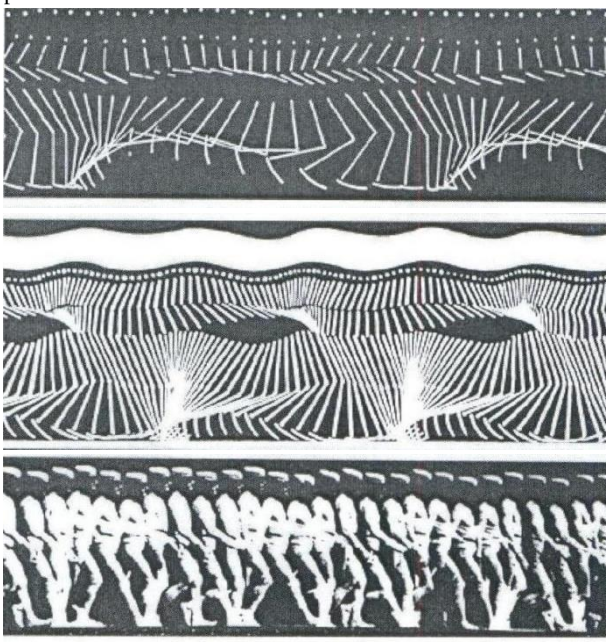


Fig. 9. Consecutive rapid photographs of human locomotion and their schematization, taken as early as the last century by Muybridge [19]. The periodic nature of the movement of each point of the body is noticeable.

The condition for the synchronous operation of the synthesized mechanisms is the connection in time of the motion of the individual motors of the mechanisms that make up the mobile robot.

$$\varphi x(t)=f(t)$$
$$\varphi u(t)=m(t)$$
$$(7)\qquad \varphi y(t)=g(t)\qquad \varphi v(t)=n(t)$$
$$\varphi z(t)=h(t)$$
$$\varphi w(t)=k(t)$$

where φ(t) – represents the laws of motion of the motors of the synthesized mechanisms in the individual directions (of the individual kinematic pairs) deployed in time.

Different types of motors realize a different type of motion, which is set with the task assignment. In this way, the task is fully defined, since it is known by what means what to achieve.

3. CONCLUSION

In conclusion, some conclusions can be drawn from the above:

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1. Any continuous periodic curve, up to the second derivative inclusive, can be considered as a type of gait of walking (in a single-phase or multiphase environment).
2. The difference between gaits by type lies in what and how many simple orthogonal curves are contained in them.
3. A kinematic chain can be broken down into multiple component kinematic chains driven by separate actuators, but when it comes to locomotion, synchronization makes them act as a single mechanism driven by a single engine.

In practice, the spatial periodic curve of the contact point of the walking mechanism during locomotion is obtained as a sum of the spatial periodic curves that are obtained from the end links of the individual actuators of the leg mechanism and of the entire walking mechanism.

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