ABSTRACT

Relevance of the Study. Contemporary trends in the advancement of mobile robots underscore an escalating interest in novel forms of walking robots posited as a viable alternative to mobile platforms reliant on wheeled or tracked mechanisms. The aspiration to harness the advantages inherent in ambulatory movement has perennially captivated the scrutiny of scholars and practitioners alike. Presently, the manifold benefits afforded by walking mobility in traversing intricate topographies are widely acknowledged, precipitating a burgeoning inquiry into walking-based propulsion systems. A bipedal robot possesses the capacity to traverse obstacles through a process colloquially termed "stepping over," thereby augmenting its navigational prowess. In contradistinction to conventional wheel or track configurations, the appendages of a walking robot encounter nominal resistance from the surrounding terrain during ambulation, virtually obviating the prospect of immobilization and, in numerous instances, enabling operational functionality with minimal traction requirements on the ground. Moreover, the modus operandi of walking locomotion serves to mitigate ground pressure, thereby reducing it substantially vis-à-vis tracked vehicles or, particularly, wheeled counterparts. The escalating enthusiasm surrounding walking robots is further evidenced in concurrence with the exponential growth of agricultural robotics, as these ambulatory platforms inflict minimal perturbation upon the supporting substrate. The discrete track pattern, characteristic of bipedal locomotion, engenders a diminution in soil erosion and effectively mitigates the risk of ravine formation, thereby attesting to the favorable ecological footprint of walking propulsion systems.

Therefore, the utilization of walking locomotion becomes indispensable for operations in disaster zones. In addition to high traversability and adaptability (the ability for smooth movement of the vehicle's body despite terrain irregularities), another inherent advantage of walking robots is associated with the particular manner in which their support limbs interact with the supporting surface. This includes the capability to navigate terrain with low load-bearing capacity and minimal damage inflicted upon the supporting surface by the robot's limbs.

Leading groups in the field of research and development of walking robots include: Boston Dynamics (USA), Ghost Robotics (USA, Philadelphia), the Robotics Laboratory at Case Western Reserve University (USA), Massachusetts Institute of Technology, A.A. Blagonravov Institute of Machine Science of the Russian Academy of Sciences (Moscow), Volgograd State Technical University, FNPC "Titan-Barricades", JSC "Titan" (Russia), Tokyo Institute of Technology (Dept. Of Mechano-Aerospace Engineering, Japan, laboratories of Professors Shigeo Hirose and Eduardo Fukushima), University of Tokyo (Dept. of Mechano-Informatics, group of Professor Noriaki Takasugi), German Research Center for Artificial Intelligence (Germany, Deutsches Forschungszentrum für Künstliche

Intelligenz GmbH, Robotics Innovation Center), FZI Research Center for Information Technology (Karlsruhe, Germany), Chinese defense company "NORINCO", Shanghai Jiao Tong University (China), Institute of Technology and Engineering (Changchun, China), University of Cassino (Italy, group of Professor M. Checcarelli), Italian Institute of Technology (Genoa, Italy, Advanced Robotics Department). Detailed review material is presented in the monographs of Professor Marco Checcarelli (University of Cassino, Italy), Professor Kenneth Waldron (Ohio State University), G. Genta (Germany), and in a number of specialized issues of the international journal "The International Journal of Robotics Research."

Traditional approaches are based on active coordination of motor functions and entail a complex hierarchical control system. Additionally, motors operate in modes of intense acceleration and deceleration, resulting in unreasonably low efficiency. Prioritizing considerations of economy, simplicity, and accessibility of technical means highlights the impracticality of universal designs. The structural irrationality of most walking robots (WR) is also linked to structural redundancy and multiple static indeterminacies. The number of active actuators in such systems far exceeds the number of degrees of freedom of the system. For instance, anthropomorphic WRs, striving to replicate human bipedal walking and running, employ dynamic gaits and are highly expensive despite achieving remarkable results (e.g., bipedal WRs like Atlas and others). The same largely applies to quadrupedal and hexapedal structural schemes characterized by the complexity of multi-level control systems, high energy consumption to support the weight of the body, and reversible motor operation modes.

An alternative to "biomorphic" designs is the utilization of orthogonal motion schemes. Such motor division is crucial for enhancing efficiency and simplifying control systems. Copying or orthogonal motors possess all the advantages of insectomorphic motors (representing open kinematic chains); meanwhile, they boast several additional benefits. In these motors, the primary linear translational motion of the vehicle body is carried out by the main motor, with the weight load from the body only borne by the motor locking device. However, the drawback of such motors lies in the use of reciprocating-translational drives and significant lateral loads in translational pairs. Employing rectilinear-guiding mechanisms allows for kinematic decoupling of motion and division of motor functions: the main motor is responsible for linear-translational motion of the body, another group of actuators is responsible for adapting to uneven terrain, and a third group is responsible for turning and maneuvering. Copying mechanisms of pantograph type are considered promising, as they allow for relatively simple adjustment of trajectory height and provide a linear transmission ratio between input and output generalized coordinates. For example, the walking robot "Adaptive Suspension Vehicle" designed by Professor K. Waldron and others is constructed in this manner. Drawbacks of such designs include significant force effects on actuating elements and the use of translational pairs loaded with lateral force.

Based on the above, the issue of optimal design of the walking apparatus and its propulsion system remains **pertinent** in terms of minimizing energy consumption and simplifying control (thus enhancing the speed of the control system).

- **The aim of the study** is to develop methods for synthesizing mechanism**s** of a walking robot's leg and optimizing the robot's parameters based on the functional decomposition, which simplifies the control system and ensures movement across rough terrain with minimal energy consumption.
- **Research object**: a high-mobility walking robot.
- **Research subject**: optimal structural-parametric synthesis of the kinematic scheme of a walking robot.
- **Research methods**: methods of robot design, analytical and numerical methods of optimization, multi-criteria synthesis of machine mechanics.
- **Theoretical and practical significance** of the research: substantiation of the optimal kinematic scheme of a walking robot based on functional division of motors, leading to significant alleviation of the control system and increased efficiency of the system.

The novelty of the research lies in the development of synthesis and optimization methods for the structural and metric parameters of walking robots (WR) based on functional division of motors, which allows:

- Simplification of leg coordination and movement with minimal number of motors, lowest energy consumption, and application of straightforward control.
- Addressing the issue of adapting each foot to surface irregularities individually and independently of the main control unit.
- Resolving the problem of redundant constraints in existing designs and eliminating parasitic loads on actuating mechanisms associated with multiple static indeterminacies.
- Eliminating additional energy expenditures on foot slippage and reducing reaction forces at joints during turns. Additionally, optimization of robot turning based on isotropy criterion.

According to the research plan, the scientific investigation comprises several parts, each focusing on specific applied and theoretical aspects of the study. Research **objectives** include:

- Review and analysis of studies in the field of walking robots and analysis of the main types of actuators.
- Development of a ‘rational synthesis’ method of a walking robot based on functional decouple of actuators.
- Development of a numerical-analytical method for synthesizing a walking

robot propulsor.

- Development and testing of synthesis algorithms and programs.
- Numerical implementation and optimization of leg mechanism parameters.
- Development of a mechanism for adapting to irregularities in the supporting surface.
- Investigation of turning modes and structural-parametric synthesis of turning mechanisms.
- Design of the actuator mechanism and walking robot prototype in SolidWorks and Autodesk Inventor software.
- Development and testing of electronic control components and walking robot control system.
- Testing of walking robot functionality on the developed prototype.

The main content of the work is as follows:

In the **first part** of the dissertation, a detailed comparative analysis of global trends in the development of walking robots over recent years was conducted. Demonstrated the ‘irrationality’ of the traditional schemes. This analysis identified promising directions for further research in this field.

In the **second part** of the work, a design principle was developed based on the decouple of motor functions and ‘rational’ synthesis. The proposed principle enables the design of a WR operating optimally from a mechanical perspective, with minimal energy consumption.

The rational structural synthesis of the WR helped to eliminate the problem of redundant connections and multiple static indeterminacies in traditional walking robot designs. The proposed design principle allows for the use of a minimal number of active drives. As a result of structural optimization, the number of primary actuators has been reduced to six. Additionally, six additional adaptation drives do not participate in the main motion and their coordination is not required, as the adaptation of each leg is carried out independently (independently of others).

As a result, this leads to a significant simplification of the control system. The use of this approach allows for the parametric synthesis of WR based on known multi-criteria synthesis methods for parallel manipulators (based on criteria such as manipulability, isotropy, etc.).

A kinematically equivalent robot scheme is presented to simplify further investigations into turning modes. A model of the "safe" turning mechanism has been constructed, with stability and absence of singularity being the primary conditions for its operation.

The **second part** of the work demonstrates the application of the principle of separating actuator functions in the rational design of a walking robot. As a result, the robot moves in an optimal mechanical regime with minimal energy consumption and using a simplified control system.

- Rational structural synthesis of the walking robot (WR) eliminated the problem of redundant connections and multiple static indeterminacies in the design of traditional robots.
- The proposed design principle allows for the use of a minimal number of active actuators. As a result of constructive optimization, the number of main motors was reduced to six.
- Moreover, an additional six adaptation drives do not participate in the main movement; coordination of their operation is unnecessary as each leg adapts individually (independently of others).
- Furthermore, this approach enables parametric synthesis of the WR based on known methods of multi-criteria synthesis of parallel manipulators (using criteria such as manipulability, isotropy, etc.).
- A kinematically equivalent scheme of the robot is presented to simplify further research on turning modes.
- A model of the "safe" turning mechanism is constructed, with stability and absence of singularities being the main conditions for its operation.

In the third part:

- A new analytical synthesis method based on the least squares approximation was developed, and its numerical implementation was presented. By minimizing the deviation directly from the desired output motion, this method avoids the so-called "branching defect," which is a common drawback of existing synthesis methods. It was demonstrated that the proposed method allows for the synthesis of a mechanism with the desired transmission angle.
- A new lambda-shaped mechanism scheme was developed for use as a WR actuator with an unlimited range of adaptation of the foot to surface irregularities. The wide (theoretically unlimited) range of adaptation to irregularities, i.e., vertical leg movement, is achieved thanks to the output link of the mechanism, which undergoes rectilinear translational motion.
- An optimal leg structure was developed, characterized by high precision, optimal motion transmission, and a step cycle parameter. These were achieved through multi-criteria optimization based on the proposed synthesis method.

In the fourth part, a mechanism for adapting to irregularities was developed to ensure the absence of vertical motion (shaking) when moving over uneven terrain, thereby contributing to increased energy efficiency.

The fifth part introduces the criterion of isotropy, commonly used by other authors for the synthesis of parallel manipulators, as a criterion for optimal force and motion transmission in all directions. In this study, we applied this method for the first time to investigate and synthesize the turning mechanism of a walking robot.

- Conditions for the isotropy of the walking robot with orthogonal actuators were derived, and optimal robot configurations in terms of force and motion transmission were determined based on these conditions.
- Solutions to the isotropy equations were found, and based on the analysis of isotropic solutions, optimal metric parameters of the robot were determined.

The sixth part is dedicated to the development of a WR prototype. Several six- and eight-legged prototypes were developed, and various walking modes were tested, including tripod gait and quadrupedal gait, in different directions (forward and backward), during turning, and on irregular surfaces. The tests were successful.

The developed working prototype of the walking robot, along with publications in internationally indexed journals (Scopus, WoS, Q1, Q2, etc.), presentations at international conferences, and patent applications, demonstrate the adequacy and correctness of the results obtained in the aforementioned sections.