PROBLEM OF METAMORPHIC STRUCTURES IN SERVICE ROBOTICS

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Recent trends in the development of robots confirm that the concept of metamorphic – self-regulating structures has found its recent form in theoretical as well as practical robotics. This development direction is topical also for service robotics where the effects of this concept can be used more intensively in the benefit of utility features of service robots. The paper shows theoretical and design approaches to the solution of metamorphic service robots. It gives selected specific questions and problems connected with its design and construction. It submits the studies and designs of service robots solved on the principle of metamorphic – self-regulating structures.

Keywords
robot, functional structure, kinematic structure, ametamorphic structure, module

1. Introduction

Dynamic development of service robotics, but mainly its massive expansion into the wide range of service and non-service activities has required the innovation of the existing approaches to the construction of mobile service robots (MSR) based on the spread of the kinematic structure of its locomotion (movement) parts and the control of the change of the function (behaviour) of the locomotion parts. The classical design of the locomotion parts does not cover recent requirements on the flexibility of MSR towards the change of the task and environment. As a possible way of solving it, a theory of mechanisms with variable structure has been worked out into the application form of *metamorphic – self-regulating structures* of MSR, mainly the structures of their subsystem of mobility. This way gives MSR a new quality (construction and the range of structures, change of locomotion function, change of features and parameters of locomotion parts) which has been based on controlled reconfigurability of their kinematic and functional structure, by which new limited variants of MSR with required new features and parameters have been created, using the original modules of MSR.

2. Metamorphic structures of service robots

Theoretic robotics characterises metamorphic robots as modular systems with the ability to self-reconfigure their own kinematic and functional structure to create a „new" robot with different functional features and technical parameters flexibly.

One of the main functions of MSR is the locomotion function, i.e. mechanic relocation of MSR within some space. MSR movement is understood as the change of status in the space (position and orientation) of MSR. MSR relocation into the status *B* in relevant (referential) space *Z* is the demonstration of certain type of relation of the movement *M* in the space *Z*.

$$M(B;Z) = \vartheta \qquad (1)$$

MSR movement can be described by a twelve-component vector expression (x_E, y_E, z_E) – position of the center of gravity connected with a non-mobile coordinate system (i_E, j_E, k_E); u, v, w – speed of the movement of the center of gravity connected with the body of a service robot; Θ, φ, ψ – Euler angles; p, q, r – angle speed connected with a mobile coordinate system).

$$X = \left(x_E, y_E, z_E, u.v, w, \theta, \varphi, \psi, p, q, r\right) \qquad (2)$$

Functional and locomotion features of MSR, in relation to the effect of the demonstration of locomotion mechanism (kinematic – locomotion chain) of the robot M_L (superposition of the movements of discrete locomotion elements of the locomotion mechanism), can be described of the locomotion function F_M (locomotion equations). The function expresses the relation R_M of the function M_L and the space *Z*. The above said can be also described by the values of characteristic parameters X_1, X_2, ..., X_n of different elements of kinematic structures of locomotion mechanism of MSR, generated by relevant drives on the base of control instructions.

$$R_M\,(M_L;\,Z) = \vartheta_M = F_M\,(X_1, X_2, \ldots, X_n) \qquad (3)$$

System model of MSR sets that the output of locomotion mechanism M_L is bound with the chassis (mobility subsystem) *CH*, their mutual connection is given by the relation R_{CH} (sum of the movements of different elements of locomotion mechanism – MSR movement).

$$R_{CH}\,(CH;\,M_L) = \vartheta_{CH}\,(4) \qquad (4)$$

Taking into account the locomotion function of MSR, the relation R_B of MSR into the status *B* and the chassis *CH* is similarly defined as

$$R_B\,(B;\,CH) = \vartheta_B \qquad (5)$$

consequently the status *B* of MSR in the space *Z*, in relation ϑ_{CH}, ϑ_B (relations can be constant or variable) is a superior function φ of the kinematic function F_M

$$R\,(B;\,Z) = \varphi\,[F_M\,;\,\vartheta_{CH}\,,\,\vartheta_B] \qquad (6)$$

while standard MSR have constant relations ϑ_{CH}, ϑ_B. Generally speaking, function F_M realization is given by the features of locomotion mechanism of MSR with a defined character of its mobility (principle of physical realization).

In given circumstances, MSR reconfigurability means the development of locomotion structures of MSR (MSR locomotion structures of locomotion mechanism) by the control of the variability of the relations R_{CH} and R_B within the system structure of the robot mobility subsystem, the development of increasing/decreasing the number of elements realizing the locomotion function F_M, the development by increasing the share of active members (at the expense of the passive ones) on the final mobility of the kinematic chain of the locomotion mechanism.

Reconfigurable MSR (metamorphic MSR – MMSR) are based on modular structure, Fig. 1, i.e. on the set of autonomous modules AM (set of locomotion, mechanical, control, ...modules) and their mutual organization and connections. By the change of mutual organization (serial, parallel, combined structures) and the connection of *AM* it is possible to construct different functional and kinematic (open, close, combined kinematic chains) of the robot configuration.

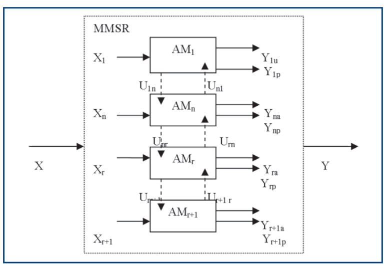


Figure 1. *System setting of modular structure*

The inputs into the module AM_{r+1}, Fig. 2, are the following: parameters X of the task of MMSR transformed into the parameters X_{r+1} of the partial task of the module X_{r+1}, parameters of compatibility U_{rr+1} transformed as the interaction of directly connected following module AM_r in the structure of MMSR. The outputs from the module AM_{r+1}

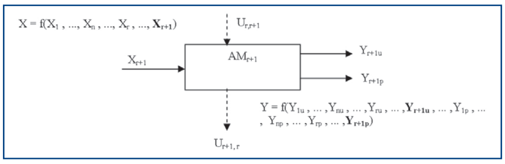


Figure 2. *Module characteristics*

are the following: output parameters Y_{r+1u} a Y_{r+1p} of the module AM_{r+1} representing fulfilling of the partial task of the module transformed into the output parameters Y of the robot MMSR, parameters of compatibility U_{r+1r} by which the module AM_{r+1} directly influences directly connected following module AM_r in the structure of MMSR.

MMSR structure functionality sets the mutual relation of AM, based on their organization in the system structureψ of MMSR directing the way and the order of their functions. The possibilities of the connection of the modules AM_i and AM_j are able to be described by the MMSR$_s$ system structure matrix (matrix type n x n, where n is the number of modules $AM = \{AM_1, AM_2, ..., AM_n\}$ creating MMSR, while the set of binary relations $x = \{x_1, x_2, ..., x_n\}$ in the set of AM is expressed by $x_{ij} = 1$ if there exists the possibility to connect AM_i and AM_j , or $x_{ij} = 0$ if there does not exist the possibility to connect the modules).

$$\mathrm{MMSR_s} = [\mathrm{AM}, \mathrm{x_i}] \tag{7}$$

By connecting the modules $AM = \{AM_1, AM_2, ..., AM_n\}$ it is possible to set MMSR with no or several degrees of flexibility. In relation to the defined coordinate system, MMSR locomotion options can be analyzed from the locomotion matrix $MMSR_{pb}$ (matrix type n x n, where n is the number of modules $AM = \{AM_1, AM_2, ..., AM_n\}$ creating MSR, while $b_{ij} = 0$ if there is not possibility of connection between AM_i and AM_j, or. $b_{ij} = 0$ if by connection of the modules there can be created a whole without locomotion options).

$$\mathrm{MMSR_{pb}} = [\, \mathrm{b_{ij}}] \tag{8}$$

Module AM is defined as a unified structurally, functionally and constructionally independent unit (constructed from the elements E; mechanic module, servodrive, or also the source, control and communication module) with given level of function integration (main, secondary, help) and intelligence (control – integration, control and decision-making function), with the ability to connect mechanically and to control other modules into functionally superior wholes.

$$MMR_\psi \approx \sum_{j=1}^{a} AM_j \approx \sum_{j=1}^{a}\sum_{i=1}^{e_j} E_{i,j} \tag{9}$$

According to the importance regarding MMSR functions, AM modules can be classified as the main ones (they secure the main function, number of modules l of the total number of modules a, e.g. locomotion modules), secondary ones (they secure secondary conditional function, number of modules $m - l$ of the total number of modules a, e.g. connecting module), help ones (they secure help function, left number of modules from the total number of modules a, e.g. a carrier). Consequently MMSR can be described by a set of modules AM according to their importance regarding MMSR functions.

$$MMR_\psi = \sum_{j=1}^{l} AM_j + \sum_{j=l+1}^{m} AM_j + \sum_{j=m+1}^{a} AM_j \tag{10}$$

From the point of view of the application, metamorphic structures can be applied on the level of the inner structure of MMSR (by reorganizing its own modules, the robot can change its kinematic structure, functional structure and disposition setting, functional features and technical parameters), or on the level of outer structure of the application of robotic system (simple robots integrate into one, functionally higher level robot or a complicated robot disassembles into a group of simple, more active and more effective robots).

3. Construction approach to metamorphic service robots

The fundament of MMSR construction is AM module. The construction and features of AM module depend on the requirements on its functionality, which follow the concept and task of MMSR. AM construction module characteristics is based on:

- own and transferred module locomotion functions: shift, turn, shift and turn;
- own module structure: heterogeneous, homogeneous;
- setting its position and possible ties in the structure of MMRS: grid, chain structure;
- number of own degrees of flexibility;
- character of own locomotion expression: linear, rotary;
- type and construction of own connecting mechanism.

Given features set the module AM module ability of metamorphosis and consequently they set also functional features and parameters of MMSR itself.

MMSR construction is based on a set of autonomous modules AM, the set can be reconfigured into various variants of settings given by the abilities of modules AM. The MMSR can be solved constructionally as:

- heterogeneous, MMSR set is created from different types of modules AM. The position of each AM module in the set is given by its features and functional possibilities, in the case of malfunction or damage of the AM module, it is necessary to change it. MMSR based on this principle is constructionally simple;
- homogeneous, MMSR set is created from the same (identical) modules AM. The position of each AM module in this set is not set by its features and functional options but its position in the structure of MMSR set(e.g. it can have the function of a „leg" or „body" with walking MSR). The modules are mutually replacable in the case of malfunction or damage of AM module, they can be replaced by another module, which is not being used at the moment of the locomotion function. MMSR based on this principle is constructionally demanding, each module has to have its own control, energy source, sensor and communication ties. However, operation of such MMSR is effective.

A set of modules AM in the structure of MMSR can be designed as following:

- chain structure (inspiration in the structure of biological models, e.g. snake, spider, insect), Fig. 3b, AM modules are lined in serial setting (central control of modules, central control and coordination of locomotion), by rearranging (reconfigurability) they can divide and create a new set according to the needs of the task, which MMSR is about

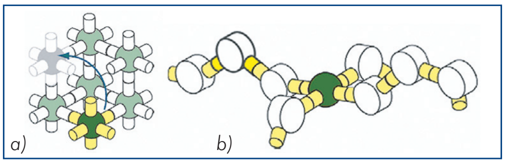


Figure 3. *MRS type structures: grid (a), chain (b)*

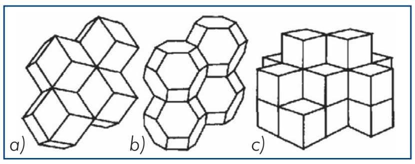


Figure 4. *Possible shapes of modules, diamond dodecahedron (a), slanted octahedron (b), regular cube (c)*

to perform. The set allows to copy locomotion functions and the features of biological models (able to be used mainly for solving the walking MSR), reconfigurability of the set allows the creation of new kinematic structures of MMSR locomotion mechanism with new locomotion features (combination of artificial and biological principles of locomotion, e.g. „leg" – „wheel"). The structure is characteristic by: complicated rearranging, simple generation of motions, low rigidity of created mechanism;
- grid structure (inspiration in the structure of materials and organic substances), Fig. 3a, a MMSR set is created by rearranging AM modules into new sets, i.e. new MMSR structures. MMSR construction is based on the principle of homogeneous set of modules AM. The structure is characteristic by: simple rearrangebility, ability to generate complicated motions, need of high number of drives and connecting mechanisms.

For the technical practice of the MMRS construction it is recommended to combine the above mentioned structures, by which it is possible to secure the task of MMSR using the advantages of both types of structures (Fig. 4).

In the MMRS construction, *connecting* mechanism has a distinctive position, it influences the type and degree of reconfigurability of MMRS. Technical possibilities of its solution are based on the principle of automatic reconstruction of modules *AM*, or on manual reconstruction. As for the concept, the mechanism can be solved as „male" – „female" or hermaphrodite with oriented or non-oriented setting. The solution also includes securing the necessary energetic performance for the connection or disconnection. Recently, the most frequently used one is the mechanism with the support of SMA (Shape memory alloy), mainly for disconnection of the modules.

Energetic securing of the module *AM* function is lately based on using Li – batteries built within the module itself. However, the development trends show that energetic securing will be realized through the connecting mechanism (energy distribution according to the module needs) from the central energetical module, the advantage of this solution is the possibility to recharge through the recharging stations.

MMRS control should solve the identification of *AM* modules in the MMSR set and the cooperation of locally connected modules *AM* so that the global MMSR task is fulfilled. The solution of given problems is based on:
- autonomy on the level of energetic securing (dependance: without autonomy – the source is not connected with MMSR, connection by a cable; low autonomy: sources in the modules, necessity to recharge; high autonomy: ability to connect to the recharging station; full autonomy: ability to find the source of energy in each application environment), on the level of control (dependance on the control form: without autonomy – control by an operator; low autonomy: performance under the control and input of the operator; high autonomy: performing tasks individually, accepting new orders for performance through the input of the operator; full autonomy: performance and task performance control individually without the operator interference);

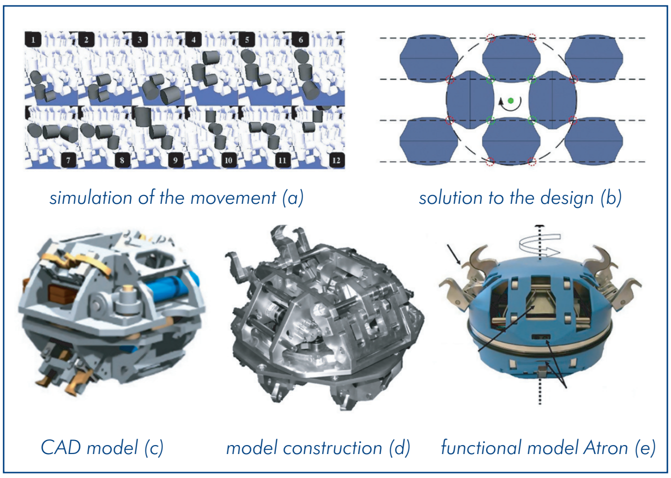
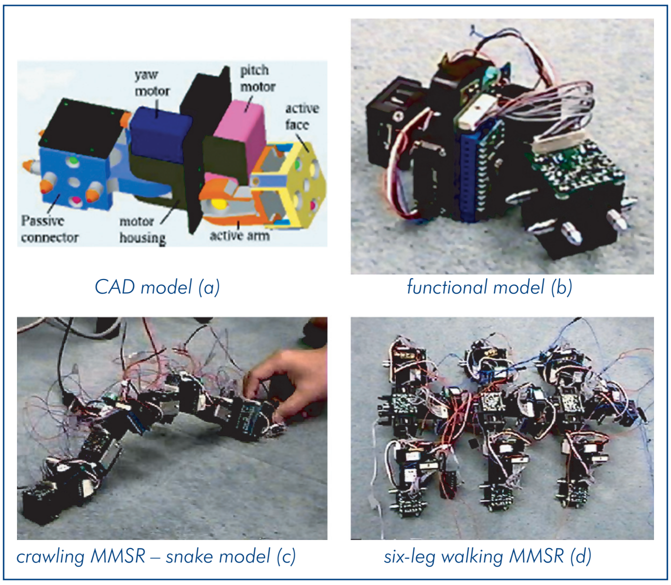

simulation of the movement (a) | solution to the design (b)
CAD model (c) | model construction (d) | functional model Atron (e)

Figure 5. *Model ATRON*



CAD model (a) | *functional model (b)*
crawling MMSR – snake model (c) | *six-leg walking MMSR (d)*

Figure 6. *Reconfiguration of the model CONRO*

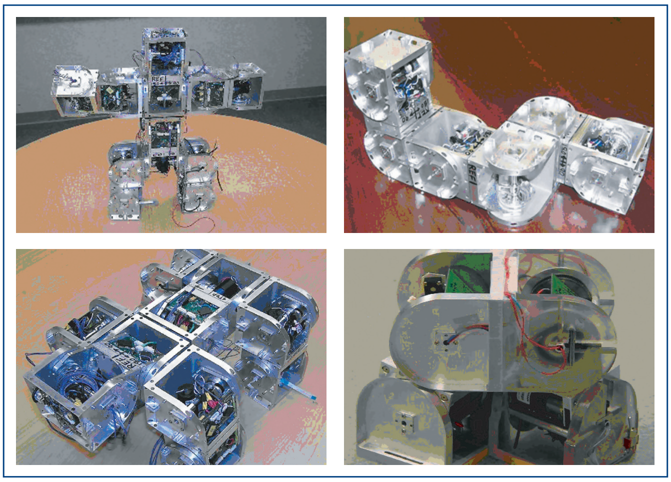


Figure 7. *Example of use of modules SuperBot*

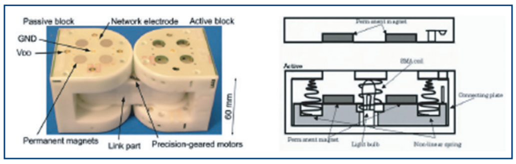


Figure 8. *Module M-TRAN, detail of its connecting mechanism*

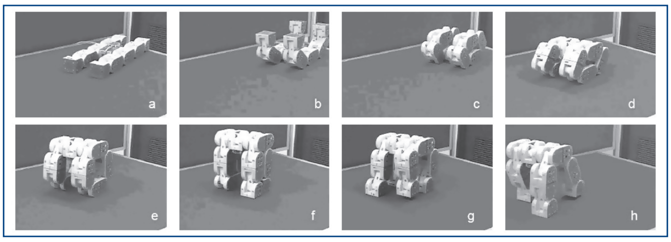


Figure 9. *Example of the possibility of reconfiguration of M-TRAN model*

- form of control of MMSR, which can be based on central control (all operations, control are solved in one place, modules are provided by the orders to fulfill tasks), or on decentralized control (from the center the orders to perform tasks are distributed and the performance of the operation is realized by the addressed level) or on the direct control by the operator. The content of the control is controlling the locomotion mechanism of MMSR, control of the change of MMSR configuration, control of task giving and the instructions for their performance, correction of activities on the base of the principle of feedback. Coordination of the activities of *AM* modules in the MMSR set must be distributed (covering whole set of modules), dynamic (coping with the changes), asynchronous (compensation of the insufficiencies of global approach), degree-like (support of the sequence of the change of shape, activation of local action elements), reliable (renewal of local malfunctions, repair securing). MMRS programming can be realized by the form „from down up" (given objective of MMSR divides into the tasks of modules *AM*), by the form „from up down" (tasks of modules *AM* transform to the effect of whole MMSR). MMRS control on the base of chain structure is performed by using: locomotion tables, neuron networks, central generator. MMSR on the base of grid structure are controlled by permanent metamorphosis.

4. Examples of the design of metamorphic service robots

Recent practice offers several solutions to the design of MMSR, from the solutions of theoretical character up to the solutions of the models for concrete technical application.

Model *ATRON* (Fig. 5) is a 3D homogeneous system constructed of two parts controlled by one joint perpendicular to the central axis. The modules have tengencial connectors (each half has two „females" and two „males"). The configuration changes by perpendicular connection of rotary axes and the rotation around one axis in 90^0, the communication is based on IR devices integrated in the connectors.

Model *CONRO,* (Fig. 6) module of this *MMSR* can fluently individually work for 35 min., connection of modules into sets is automatic. The connection process has the phases of adjustment and synchronisation of sensors, the phase of creating contact (IR receivers, inverse kinematics) and the phase of hardening the connection (safety pin).

Model *SUPERBOT* (Fig. 7) is homogeneous MMSR designed for space research. System module is designed to be fully autonomous, mobile, it has an ability to identify own modules and consequently join them into higher level sets.

Model M-TRAN (Fig. 8) allows movement in 3D space, the module construction includes two servomotors controlling two main locomotion functions, connectors are designed on the principle of permanent magnets, microprocessor is incorporated within the module. The model is markedly reconfigurable, which allows it to create new sets fluently and by this change the form and character of movement.

Use of the principles of metamorphic structures in construction of the details of locomotion mechanism of MMSR can be presented on the design of metamorphic wheel, model EGON (designed at the workplace of the author). By the inner construction of its parts (modules) and the possibility to control the change of their arrangement it can fulfill the function of a „wheel" or a „belt". The application of the model with wheeled MMSR gives the robots new driving abilities which can be adjusted to the requirements of the terrain.

5. Conclusions

The problem of the design and application of MMRS has become a highly recent topic for theoretical as well as practical robotics. It echoes the dynamics of the service robotics development and searching new technical designs of the MSR construction for the applications into non-traditional, demanding environments. The trends of the application of *metamorphic – self-regulating* structures in the design of mobility of MSR susbsystem, on the base of existing results and their evaluation, have proved technical usability and suitability to design new requirements on MSR. So it can be concluded that the problem of MMSR has the reason to be solved also in our conditions.

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