INVESTMENT AND RUNNING COSTS ESTIMATION FOR HETEROGENEOUS MULTI-ROBOT SYSTEM

VITALIJS KOMASILOVS

Department of Computer Systems, Latvia University of Agriculture, Latvia
vitalijs.komasilovs@gmail.com

Abstract: *Economic benefit of an industrial company depends on forethought deployment of an industrial production system. Authors propose the procedure for optimization of specification of multi-robot system. It uses following concepts: mission requirements are defined using components –functions of the robotic system. Components are grouped into agents – mobile robots or stationary units of a robotic system. Finally a set of agents is considered as a solution – a specification of heterogeneous robotic system, which defines types of agents and a number of their instances used to carry out a mission. The paper describes the analysis of investment and running costs of heterogeneous multi-robot system and presents development of costs estimation model used as a fitness function in genetic algorithm.*

Keywords: multi-robot system; optimization; genetic algorithm.

Introduction

Application of robotic systems in various fields is gaining popularity. Robotic systems are being used on industrial sites for production process automation (Jammes & Smit, 2005) and intelligent manufacturing (Almeida, 2011). An increasing number of applications is reported in such domains as medicine (Davies, 2010), elderly care (Hansen et al., 2010) or daily life as household companions (Parlitz et al., 2007). During the years researches have noticed variety of advances of heterogeneous robotic systems comparing with convenient ones (Weiming Shen & Norrie, 1999; Bi et al., 2008). Increasing number of applications of heterogeneous robotic systems (Kiener & von Stryk, 2010; Medvidovic et al., 2011; Wong et al., 2011) set the complex task of design and development of optimal heterogeneous robotic system. The effectiveness of production system and economic benefit of a company depends on successful deployment of industrial robotic system.

Current researches are aimed to improve performance of heterogeneous robotic system using variety of novel methods applied for intelligent control (Nouyan et al., 2009; Parker, 2008), world modeling (Coltin et al., 2010), communication (J. E. Haddad & S. Haddad, 2004; Rybski et al., 2007; Mathews et al., 2011), etc., but the configuration of the system is predefined or selected intuitively. However the performance of whole system is strongly influenced by characteristics and functionalities of the individual robots (Levi & Kernbach, 2010). Author proposes an optimization procedure, which is based on heuristic search methods, and its purpose is to reduce the space of feasible solutions and to identify non-optimal combinations at early stage with minimal effort.

The paper describes costs estimation model for heterogeneous robotic system which is used for initial evaluation of solution candidates and is implemented as fitness function for genetic algorithm. Genetic algorithm was introduced as powerful, domain-independent heuristic search technique inspired by Darwinian theory (Holland, 1975). Successful applications of genetic algorithm were reported in variety of domains, which include chemistry (Zhong & Tian, 2011), management (Gonçalves et al., 2008), logistics (Sourirajan et al., 2009), control (Jiang & Adeli, 2008). Researches demonstrate optimization of various parameters of robotic system (Martínez et al., 2009; Hondo & Mizuuchi, 2011; Saravanan et al., 2009). Author use total costs of ownership (TCO) as a universal criterion for multi-robot system applied at analysis and design stage of the project. TCO includes costs required for design, implementation, deployment and operation of such system. The aim of described costs estimation model is evaluate large number of solution candidates within reasonable amount of time.

Concept of specification optimization procedure

The scope of current research is limited to heterogeneous multi-robot systems domain and it aims to develop a formal method for optimization of specification of multi-robot system. Multi-robot system specification is a formal description of system’s configuration. The specification defines types of agents (classes), their functions as well as a number of instances of each class of agents in the system. Optimal specification of multi-robot system is such configuration of the system, which maximizes objective function. Author is selected total costs of ownership (TCO) which is convenient criterion for robotic systems as it includes design, development and operating costs of system.

According to developed specification optimization procedure several concepts has been defined (see Fig. 1.). *Component* stands for a definition of function of the robotic system. Components are grouped together in order to form an *agent* (rather, mobile robot or a stationary unit). *Solution* is a specification of heterogeneous robotic system, it defines types of agents and a number of their instances used to carry out a mission. Number of rules is applied before considering any combination of agents as a solution. Complexity analysis demonstrates that combinatorial explosion is typical for such types of optimization problems.

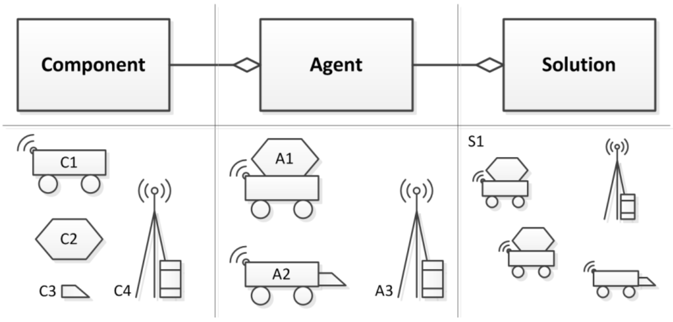

Fig.1.**Conceptual model of the solution**

Specification optimization is performed according to developed procedure, which specifies five consecutive steps (see Fig.2.). First of all business requirements are defined by industrialist, then optimization objective function is developed and solution space is analyzed. If the number of possible solutions is too high to evaluate all of them, then heuristic algorithms are used to narrow the scope of considerable options to the bunch of fittest solutions. Finally evaluation is performed using simulations in order to select optimal solution for particular mission. Detailed description of steps of the procedure is provided in (Komasilovs & Stalidzans 2012).

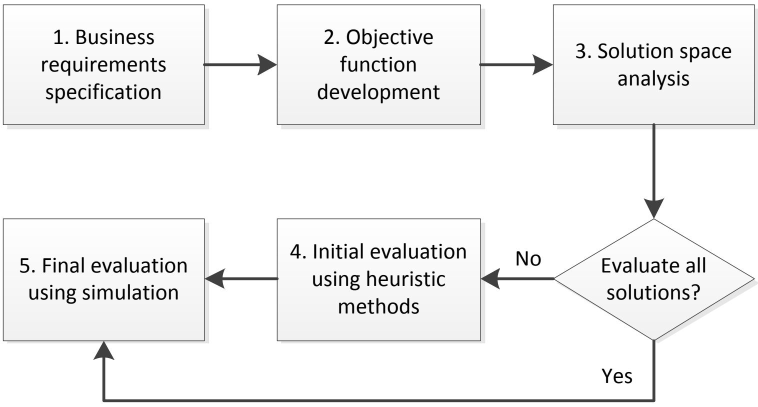

Fig.2. **Specification optimization procedure**

The scope of this paper is limited to step 4 of the specification optimization procedure and it describes TCO estimation model used for initial evaluation of solution candidates.

Estimation of investment costs

Within the current paper author use term investment costs to define all expenses required to design, implement and deploy multi-robot system from the scratch into production environment. Investment costs do not include expenses related to the operation of the system.

Simple model has been developed that allows fast estimation of investment costs and fast evaluation of solution candidates. Investment costs could be divided into several positions described below. Conceptual model of multi-robot system specification optimization procedure imply that the mission for such system is defined using a list of components. Costs estimation model assume that components have additional properties, which are related to the costs of particular component.

Proposed model imply that investment costs of the whole system (Q_{inv}) equals to the sum of investment expenses for agents (Q_{inv_agent}). Additionally expenses for system design are applied as a fraction of agents' expenses (c_{sys_design} coefficient).

$$Q_{inv} = (1 + c_{sys\_design}) \times \sum Q_{inv\_agent} \quad (1)$$

Investment costs of agents (Q_{inv_agent}) consists of design costs of particular type of agents (Q_{design}) and production expenses (Q_{prod}) of all instances of particular class of agents.

$$Q_{inv\_agent} = Q_{design} + Q_{prod} \times N_{inst} \quad (2)$$

Design costs (Q_{design}) depends on the number of components (N_{comp}) involved into design of particular type of agents, and author assume that it grows exponentially. Coefficients (c_{lin} and c_{exp}) are used to tune growth dynamics according to real prices of design.

$$Q_{design} = c_{lin} \times exp\left(c_{exp} \times N_{comp}\right) \tag{3}$$

Production costs of an agent (Q_{prod}) equals to sum of purchase prices of components (Q_{comp}) used in particular agent and agent assembly expenses (Q_{assy}).

$$Q_{prod} = \sum Q_{comp} + Q_{assy} \tag{4}$$

Assembly costs of an agent (Q_{assy}) grows exponentially depending on number of components used in the agent (N_{comp}). Author assume that each component have additional complexity index (c_{cplx}), which should be involved into assembly costs calculation.

$$Q_{assy} = c_{lin} \times exp\left(c_{exp} \times N_{comp}\right) \times \max\left(c_{cplx}\right) \tag{5}$$

Values of Q_{comp} and c_{cplx} are defined for each component used in multi-robot system specification optimization procedure, coefficients c_{lin} and c_{exp} both for design and assembly costs estimations are defined on the level of optimization problem.

Estimation of operating costs

Within the scope of current research author defines operating costs as the expenses which are required to perform particular mission specified for specification optimization procedure. Operating costs of the heterogeneous multi-robot system are highly dependent on application peculiarities of the system because of dynamic perturbations between mobile robots of different types. The most precise method to estimate operating costs for such systems are simulations, which allow reproduction of operating environment close to real production site.

The aim of the paper is to development of fast operating costs estimation model which is used to evaluate large amount of solution candidates. Author assumes several simplifications: it is considered that agents have no downtime. Agents switch from one task to another instantly, and they are utilized for 100% of time. Also it is considered that particular agent can perform only one of its functions at time.

According to proposed model operating costs (Q_{oper}) of the system consist of energy (Q_{enrg}) and maintenance (Q_{maint}) costs of equipment.

$$Q_{oper} = Q_{enrg} + Q_{maint} \tag{6}$$

Maintenance costs (Q_{maint}) of the robotic system are considered to be constant over operating time of the system (T_{sys}). It is considered that maintenance rate exponentially grows of total number of agents within the system (N_{agents}).

$$Q_{maint} = c_{lin} \times exp\left(c_{exp} \times N_{agents}\right) \times T_{sys} \tag{7}$$

Major part of operating costs of the system consists of energy expenses (Q_{energ}), like electricity or fuel costs. It depends of operating costs (Q_{oper_agent}) and operating time (T_{agent}) of each agent.

$$Q_{energ} = \sum\left(Q_{oper\_agent} \times T_{agent}\right) \tag{8}$$

Operating expenses of particular agent per time unit (Q_{oper_agent}) are calculated as sum of power consumption indicators (P_{comp}) of its components.

$$Q_{oper\_agent} = \sum P_{comp} \tag{9}$$

Working time estimation for particular agent is not trivial in multi-robot systems and it refers to logistics. It could be generalised as transportation problem where agents are capable to perform certain tasks with defined performance (suppliers). The mission for robotic system is to get completed defined amount of tasks (consumers). Additional parameters are defined for the mission in order to calculate dynamic attributes of the agents. General transportation problems are solved using linear programing, for instance using simplex method (Nelder & Mead 1965).

Conclusion

The paper presents costs estimation model for heterogeneous multi-robot system, which is used for initial evaluation of system's specification. It refers to step 4 of proposed specification optimization procedure, which is implemented using genetic algorithm. The model is used as fitness function for individuals of genetic algorithm population and it allows fast evaluation of solution candidates with acceptable accuracy.

Specification optimization procedure was developed as formal analysis method for heterogeneous multi-robot systems and it allows elimination of non-optimal solution branches on early stages with minimal effort.

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