International Journal of Engineering

The Effect of Base Position on Maximum Allowable Load of Dual Arm Robots

H. Ghariblu*, A. Javanmard

Advanced Mechatronic System Lab., Department of Mechanical Engineering, Engineering Faculty, University of Znajan, Zanjan, Iran

A B S T R A C T

A new computational technique is presented to find the optimal base position of dual arm robots in order to carry maximum allowable load. The maximum allowable load on a desired trajectory is limited by the number of factors such as; actuators torque limits, kinematic constraints, and kinematic redundancy of cooperative manipulators. For a dual arm robot mounted on a rail or table, load workspace (LWS) is introduced as the union of places where the base can locate and robots carry a load on a desired trajectory. It is possible to increase the maximum allowable load by replacing the base of the arms robots in the LWS. By dividing the LWS into grid points, the base position of the rail mounted dual arm robot considered at each point. Using the Newton-Euler formulation and appropriate procedure, maximum allowable load of the robots in all points of the LWS are computed. Then, by iteration, a smaller subspace near to optimum base position is selected until maximum allowable load and corresponding base position is found with acceptable precision. Finally, the application of the proposed algorithm is presented and verified for two different cases.

1. INTRODUCTION

A single robot can manipulate objects only as far as it can reach with limited load capacity. Most industrial robots are fixed in place, thereby limiting their flexibility for tasks requiring manipulation beyond their workspace. Assembling a robot arm over a rail or XY table can provide extreme layout flexibility and increase the size of the work envelope and reduce joint limit constraint. Railed robots are ideal for robotic applications requiring extended reach and high throughput, including machine tending, material handling, material loading, welding, deburring, trimming, and dispensing. In recent years well known robot manufacturers such as Fanuc, ABB and Yasakawa have introduced different kinds of rail mounted manipulators. On the other hand, cooperative manipulation is an important enhancement to robotic capabilities as a dual-arm robot is enabled to perform more complex tasks, manipulate greater payloads, and span a greater workspace [1, 2]. Recently, Yasakawa Motoman Company has introduced different kinds of

dual-arm robot to meet industrial automation needs. These robots might be mounted on railed or moving tables[1]. Therefore, installing two robotic arms on a railed or mobile base results a highly redundant system and increases the robotic system capability to perform difficult and complicated manipulation tasks with great ease and speed.

In this work, the effect of base position on maximum allowable load of dual arm manipulators mounted on a rail or XY table is studied,this has not been discussed by prior researchers. Finding the maximum allowable load for robotic manipulators can maximize their efficiency and performance in handling heavy objects. Usually, the main constraint for determining the maximum allowable load for a robotic manipulator is its actuators' torque limit. Meanwhile, there are other factors that can restrict the maximum load capacity as well as joint constraints, kinematic redundancies, and trajectory accuracy constraints. The issue of determining maximum allowable load of single and multi arm robot

---

*Corresponding Author's Email:ghariblu@znu.ac.ir(H. Ghariblu)

systems have been investigated by different researchers. For a single robotic manipulator, Thomas et al. [3] used the load capacity as a criterion for sizing the actuators of robotic manipulators at the design stage. Wang and Ravani [4, 5] introduced a computation algorithm of dynamic load carrying capacity based on the inertia effects of load and manipulator motion. They showed that maximum allowable load of a manipulator on a given trajectory is primarily constrained by the joint actuator torque and its velocity characteristics. In their study, maximum load is considered in the neighborhood of robot configuration. Korayem introduced a new formulation to find maximum load capacity for point to point motion of flexible link manipulators [6].

Also, Korayem and Ghariblu have studied maximum allowable load of a mobile manipulator imposing redundancy constraints[7], and stability approach [8]. They have also shown that for a single arm mobile base manipulator, there is a unique position for base of a robot arm to carry the maximum allowable load [9].

For cooperative manipulator, Wang and Kuo [10] formulated the governing dynamic equations and inverse dynamic of the multiple robot system in the joint space based on a coordinate partitioning technique. Their solution for load carrying capacity was based on optimization with solving a small-size linear programming problem, which was limited to local solutions and sensitive to initial predefined trajectory. Ghariblu and Javanmard [11] have introduced a method to determine the maximum allowable load of two arm manipulators for a desired trajectory of the load, subject to both actuator and redundancy constraints.

Section 2 briefly presents the base workspace (BWS) and load workspace (LWS) concepts. In Section 3, we formulate the kinematic and dynamic equationsof two cooperative manipulatorshandling a load. The algorithm to find optimal base position to maximize the allowable load of these robots discussed in Section 4. Finally, in two different case studies the application of the method to increase the maximum allowable rely on base position of dual arms are discussed (Section 5).

2. BASE AND LOAD WORKSPACE

The union of all positions that the common base of arms can be moved and located on them is called the BWS as shown schematically in Figure 1. There exists a subspace of BWS where the base can be located and carries a load on a desired load trajectory. This subspace is defined as load workspace (LWS) and is a function of robots type, their physical dimensions, joint limit and joint actuator constraints. These concepts have been extensively presented and discussed in our before work [6];

3. DYNAMICS OF TWO ARMS HANDLING A LOAD

Let us suppose the condition shown in Figure 2 where two arms cooperatively hold a load. Assuming that motion of the load is fully specified, configuration $r = (r_l \quad , R_l) \in R^6$ include the load center of mass position $r_l$and orientation R_l, and its time derivatives, velocity, $\dot{r} = V_l = (v_l \quad , \omega_l)^T$, and acceleration, $\ddot{r} = a_l = (\dot{v}_l \quad , \dot{\omega}_l)^T$ are known prior. Hence, the load equations of motion based on the Newton-Euler formulation have the form:

$$\begin{bmatrix} mI & 0 \\ 0 & \bar{I} \end{bmatrix}\begin{bmatrix} \dot{v}_l \\ \dot{\omega}_l \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_l \times \bar{I}\omega_l \end{bmatrix} = \begin{bmatrix} f_1 + f_2 \\ r_{c1} \times f_1 + r_{c1} \times f_2 \end{bmatrix} \qquad (1)$$

where, $m$is the load mass, I, and $\bar{I}$ are identity and moment of inertia matrices, respectively. f_1 and $f_2$denote the forces at the point acting on the load through the arms and , r_{c1} andr_{c2} are the position of the end effectors all with respect to frame attached at the load center of mass.

Solving Equation(1) for given load trajectory $r, \dot{r}$ and $\ddot{r}$ we can compute equivalent f_1 and f_2. Geometrical constraints between the given load trajectory $r, \dot{r}$ and $\ddot{r}$ and their corresponding joint variables $q_i \in R^{n_i}$, $\quad , R_i) \in R^6$, $\dot{q}_i$ and, $\ddot{q}_i$ of arm i (i = 1 for the right arm; i = 2 for the left arm), are:
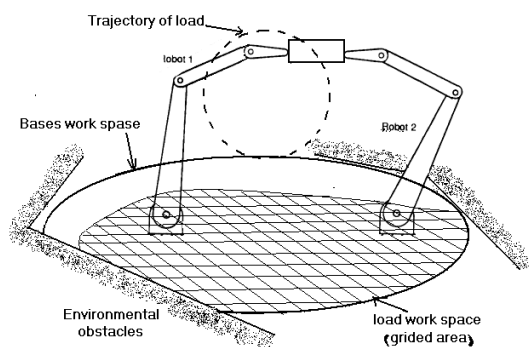
$$r = r_1(q_1) = r_2(q_2) \qquad (2)$$

where n_i is the degrees of freedomof arm i. Differentiating Equation(2) twice by time, leads to:

$$\dot{r} = J_i\dot{q}_i \quad , \quad \ddot{r} = \dot{J}_i\dot{q}_i + J_i\ddot{q}_i \qquad (3)$$

Using Equations (3), $\dot{q}_i$ and $\ddot{q}_i$ can be written as:

$$\dot{q}_i = J_i^{-1}\dot{r} \quad , \quad \ddot{q}_i = J_i^{-1}(\ddot{r} - \dot{J}_iJ_i^{-1}\dot{r}) \qquad (4)$$

where J_i is the Jacobian matrix to transform the joint velocity $\dot{q}_i$ into the velocity of the frame at the load center of mass.

Figure 1. Schematic plan of base workspace and load workspace of two cooperative manipulators on a desired load trajectory

The dynamic equation of the arm i, has the form:

$$M_i(q_i)\ddot{q}_i + C_i(q_i, \dot{q}_i)\dot{q}_i + G_i(q_i) = \tau_i + J_i^T(-f_i) \quad (5)$$

where M_i is positive definite Inertia matrix, C_i a vector representing centrifugal and Coriolis forces, G_i a vector representing the gravity load and $\tau_i \in R^{n_i}$ the corresponding vector of joint torques.

Solving the inverse kinematics and computing, q_i, $\dot{q}_i$ and $\ddot{q}_i$ from Equations (2), (3) and (4) and substituting f_1 and f_2. executed from Equation (1), joint torques τ_i are computed.
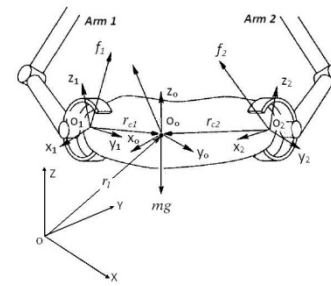
4. OPTIMUM BASE POSITION AND MAXIMUM ALLOWABLE LOAD

In this section, the computational procedure to determine an optimum base location and maximum allowable load of two cooperating arms is outlined. At the first step, the given trajectory of the load and BWS is divided into some grid points. Then, selecting an initial load with a known mass and inertia, the first point of the divided BWS is chosen as the base position. Using kinematic and dynamic equations derived in the previous section, joints variables of two arms are computed for given trajectory.

At the second step, Joints limits are checked as well as singular conditions along with the given trajectory. This base position belongs to the LWS if none of these constraints, are not violated.

Then, total dynamic effects of the load and manipulators on the joint torques τ are computed. Neglecting the force applied to the end effectors, and substituting $f_1 = f_2 = 0$, in the system of Equations (5) the actuators torque to compensate manipulators dynamics τ_{nl} on each joint is computed. By subtracting τ_{nl} from τ, the τ_l is obtained:

$$\tau_l = \tau - \tau_{nl} \quad (6)$$

The joint actuators upper and lower bounds $T^{(+)}$ and $T^{(-)}$ have the main role in the maximum load carrying capacity of the robots. Hence, comparing τ_l with actuators lower or upper bounds we compute the load coefficient C for the selected base position, as expressed in detail in [14], and omitted here for brevity. The computational procedure to find optimal base position and maximum load is flowcharted in Figure 3.

Selecting a new small subspace of the load workspace in the neighborhood of a place where m_{load} has the maximum value, and dividing this subspace with higher resolution and repeating the above algorithm, optimal base position and maximum allowable load are found with an acceptable precision.
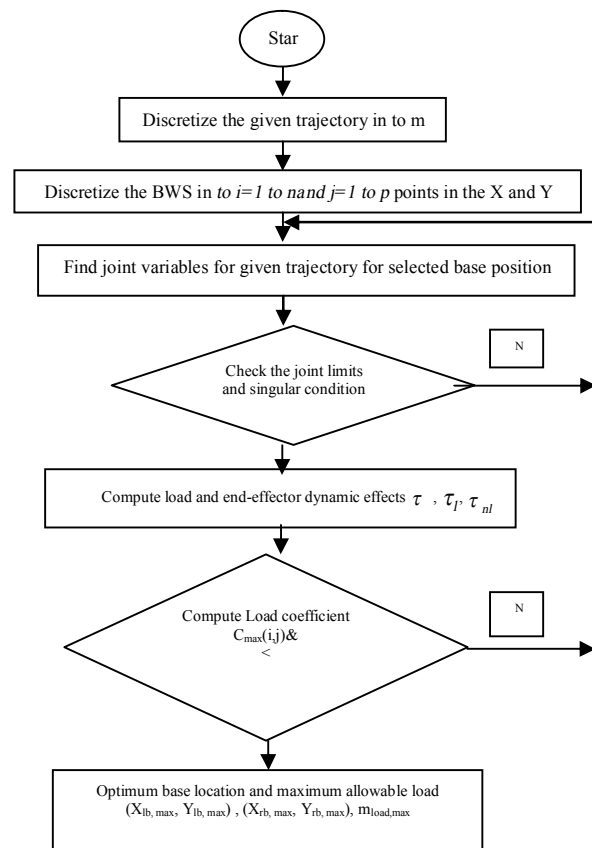

Figure 2. Two arms holding a load

Figure 3. Flowchart of determining the optimum base location and maximum allowable load of dual arm manipulators.

5. SIMULATION STUDY

Based on the method presented, two simulation studies was carried out to demonstrate the validity and productivity of the method and proposed algorithm. This algorithm determines optimum base position and maximum allowable load of rail mounted dual arm manipulators.

5. 1. Case 1. Two Cooperative Three-link Planar Manipulators Numerical simulations are performed for a rail mounted dual arm three-link planar

manipulators to carry a common load (Figure 4). Two manipulators are similar and link parameters and inertia properties of the manipulators are given in Table 1, while the motor of the actuators are permanent magnet motors. For permanent magnet DC motors, there is a linear relationship between torque and speed for a constant voltage:

$$\tau_{motor} = \tau_s - (\tau_s/\omega_n)\omega \tag{7}$$

where, ω_n=5 rad/s and τ_s=60 N.mare no-load speed and stall torques, respectively. The given trajectory is a semi-circle centered at (0.5m , 0.125m) with respect to the reference frame F_1, having a radius of 0.25m .The object is required to move along the trajectory with a constant linear velocity of 0.5 m/s and an overall time of motion oft=1.5 s.According to configuration of robots, it is assumed that the base workspace of the manipulator is a line with 1000 mm length along the X coordinates. Dividing the base workspace and given trajectory into equal points, the maximum allowable loadat each base points along the given trajectory is calculated as shown in Figure 5. The optimal base position with coordinate $X_{left,man}$=0.4 m and $X_{right,man}$=0.6 m with the maximum load 5.581 kg are found. Figure 6 shows the total torque on each joint actuatorof manipulators on the optimal base position when carrying the maximum allowable load.

Also, in some regions of base workspace it can be seen the value of the m_{load} is zero. This may arise from one of the following problems:

i) The joint limits or actuator constraints are violated.

ii) A singular condition occurs when the robot tries to move along its given path.

Therefore, the mobility of the base is an effective way to avoid the joint limits, actuator constraints, and other kinds of singular conditions.

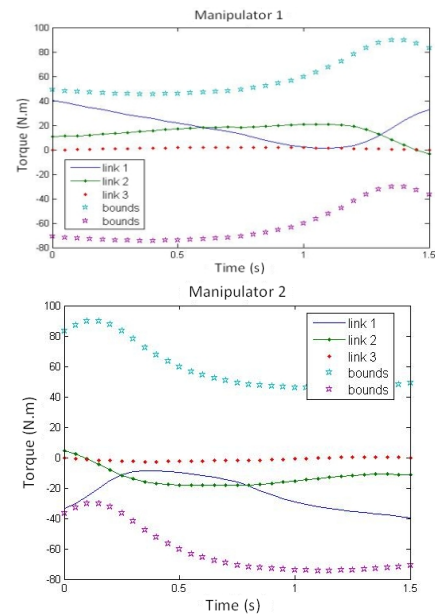**TABLE 1.** link parameters and inertia properties of the manipulators

Moment of inertia $(Kg.m^2)$	Length (m)	Mass (Kg)	Link number
0.013	0.4	4	1
0.026	0.5	5	2
0.0002	0.1	1	3
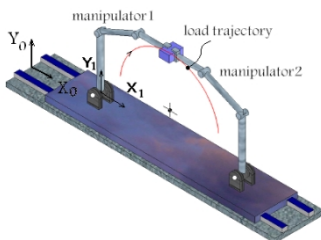
Figure 4. Two cooperative three-link planar manipulators handling a load.
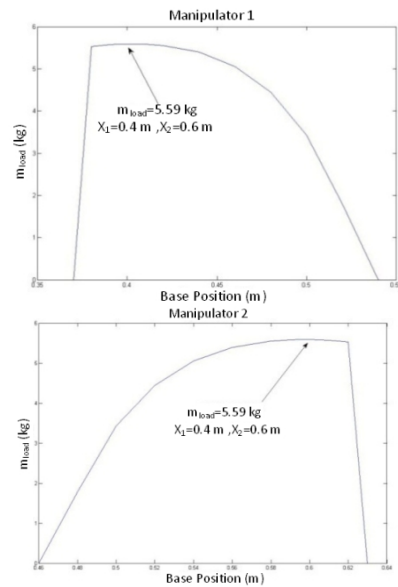
Figure 5. Diagram of the m_{load} versus base position.

Figure 6. Total torque on each joint actuatorof manipulators

5. 2. Case 2. Dual Puma Type Robots   In this case, two similar 6 axes puma robots are fixed over a X-Y table, 800 mm apart each other, and carry a common load (Figure 7). It is assumed that, X-Y table can traverse 400 mm along X direction and 300 mm along Y direction. The load path is a circle with center (-400, 0, 400) mm, and radius 200 mm with respect to the inertial reference frame attached to the middle of base work space, The overall time for this motion is t=4 sec. The link parameters of robots are listed in Table 2, while the motors of the actuators are permanent magnet motors

and their constants are given in Table 3. By dividing the base workspace in both traversing directions and the load trajectory, the maximum allowable load in all base positions along the given trajectory are calculated. At the base position (Xb=-0.4 m, Yb=0.0 m), for robot 1, and (Xb=0.4 m, Yb=0.0 m) for robot 2, the maximum load is found equal to 14.3 kg.

In the next step, a smaller subspace of the LWSin the neighborhood of the optimum base position is chosen, as shown in Figure 8. Then the optimum base location is found at the points coordinate (X_b=-0.4 m, Y_b=0.0125 m), for robot 1, and (X_b=0.4 m, Y_b=0.0125 m) for robot 2 with m_{load}=14.44 kg. In order to find the base optimum position and its corresponding maximum allowable load with higher precision, the above procedure can be repeated. Figure 9 shows the total torque on each joint actuatorof robots when carrying the maximum allowable load on the optimum base position.
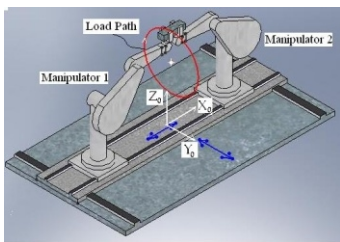
TABLE 2. Link parameters and inertia properties of puma robots

Link number	Mass (kg)	Length (m)	Moment of inertia (kg.m^2)
1	4	0.4	0.0133
2	4.5	0.45	0.019
3	1.25	0.125	0.0003

TABLE 3. Actuator constants of puma robots

Actuator number	τ_s (N.m)	ω_n (rad/s)
1	70	10
2	90	15
3	50	7
4	10	1.5
5	10	1.5
6	10	1.5

Figure 7. Two cooperative 6 axes puma robots handling a load.
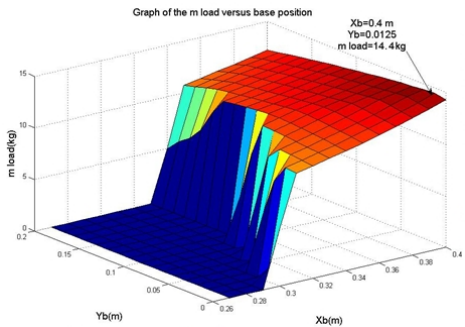
Figure 8. Graph of the m load versus base position.
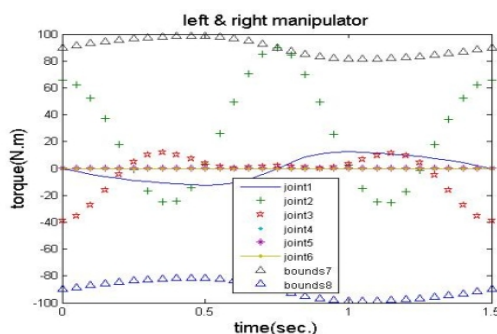
Figure 9. Total torque on each joint of robots

6. CONCLUSIONS

In this paper, a systematic approach for formulating the governing dynamic equations of a rail mounted dual arm robotic system has been presented. The concepts of base workspace and load workspace introduced for these robotic systems. A general method for computing the optimal base position to carry maximum allowable load of such manipulators is also developed. The method assumes that the payload and end effector trajectory are known prior. It is shown that maximum payload capacity of railed base dual arm manipulators is a function of their base position. Finally, in some case studies, by considering different trajectory for the load the effect of base mobility on optimizing payload capacity in the different kinds of robotic arms is investigated.

It is seen that it is not possible to locate the common base of the dual arms at some distances on the base working space and carry a load in the given trajectory. This is due to constraints on the robot joints and actuators or singular conditions in the manipulator configuration, when it tries to move in its given path. Therefore, the base mobility permits a change in the base position to avoid unwanted constraints of the robotic manipulators.

7. REFERENCES

1. Sun, D. and Mills, J.K., "Manipulating rigid payloads with multiple robots using compliant grippers", *Mechatronics, IEEE/ASME Transactions on*, Vol. 7, No. 1, (2002), 23-34.

2. Zivanovic M.D and Vukobratovic M.K., "Multi-arm cooperating robots-dynamics and control, springer, (2006).

3. Thomas, M., Yuan-Chou, H. and Tesar, D., "Optimal actuator sizing for robotic manipulators based on local dynamic criteria", *Journal of Mechanical Design*, Vol. 107, No. 2, (1985), 163-169.

4. Wang, L. and Ravani, B., "Dynamic load carrying capacity of mechanical manipulators—part ii: Computational procedure and

applications", ***Journal of Dynamic Systems, Measurement, and Control***, Vol. 110, No. 1, (1988), 53-61.

5. Wang, L.-T. and Ravani, B., "Dynamic load carrying capacity of mechanical manipulators—part i: Problem formulation", ***Journal of Dynamic Systems, Measurement, and Control***, Vol. 110, No. 1, (1988), 46-52.

6. Korayem, M., "Optimal trajectory of flexible manipulator with maximum load carrying capacity", ***International Journal of Engineering***, Vol. 8, No. 4, (1995), 221-232.

7. Habibnejad Korayem, M. and Ghariblu, H., "Maximum allowable load on wheeled mobile manipulators", (2003).

8. Korayem, M., Ghariblu, H. and Basu, A., "Optimal load of flexible joint mobile robots stability approach", ***International***

Journal of Engineering-Transactions A: Basics, Vol. 17, No. 2, (2004), 193-204.

9. Korayem, M. and Ghariblu, H., "The effect of base replacement on the dynamic load carrying capacity of robotic manipulators", ***The International Journal of Advanced Manufacturing Technology***, Vol. 23, No. 1-2, (2004), 28-38.

10. Wang, L.-C. and Kuo, M.J., "Dynamic load-carrying capacity and inverse dynamics of multiple cooperating robotic manipulators", ***Robotics and Automation, IEEE Transactions on***, Vol. 10, No. 1, (1994), 71-77.

11. Ghariblu, H. and Javanmard, A., "Maximum allowable load of two cooperative manipulators", in Computer Engineering and Applications (ICCEA), 2010 Second International Conference on, IEEE. Vol. 2, (2010), 566-570.

The Effect of Base Position on Maximum Allowable Load of Dual Arm Robots

H. Ghariblu , A. Javanmard

Advanced Mechatronic System Lab., Department of Mechanical Engineering, Engineering Faculty, University of Znajan, Zanjan, Iran

چکیده

روش محاسباتی جدیدی برای موقعیت دهی بهینه دو بازوی روباتی همکار با هدف قابلیت حمل بار حداکثر ارائه شده است. حداکثر بار مجاز قابل حمل تابعی از عوامل مختلف مانند، محدودیت گشتاور اعمالی موتورها، قیدهای سینماتیکی و درجات آزادی اضافی در روباتهای همکار است. برای دو بازو که روی یک پایه متحرک ریلی در یک محور خطی و یا دو محور خطی متعامد نصب شده، فضای کاری بار عبارت از بخشی از فضای استقرار پایه است که قابلیت حمل بار در یک مسیر از قبل معلوم را دارد. با این تعریف میتوان به محل بهینه استقرار پایه روباتها با هدف حداکثر نمودن بار مجاز در یک مسیرمعلوم تیین کرد. برای نیل به این هدف، با شبکه بندی فضای کاری بار، موقعیت پایه در هر یک از نقاط این شبکه بندی در نظر گرفته میشود. سپس، با فرمول بندی نیوتن-اویلر و الگوی محاسباتی مناسب، حداکثر بار قابل حمل در هر یک از موقعیتها محاسبه میشود. در مرحله بعد، با در نظر گرفتن یک زیر فضا در حوالی موقعیت بهینه، موقعیت نهایی پایه و ظرفیت حمل بار معادل آن با دقت مورد نظر تعیین میشود. در نهایت، با مطالعه موردی کاربرد الگوی محاسباتی ارائه شده و مورد ارزیابی قرار میگیرد.

.doi: 10.5829/idosi.ije.2015.28.02b.15