On the Modeling and Simulation of Collision and Collision-Free Motion for Planar Robotic Arm

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Abstract— *Safety functioning is considered as an important issue within overall designing process of autonomous robotic systems. A general structure of collision detection and avoidance system for planar robotic arms is proposed. Simulation results of collision and collision-free motions are presented.*

Keywords— Collision avoidance, planar robotic arms.

I. INTRODUCTION

Manufacturing, service, research, exploration and many other areas of human activity require a lot of handling operations of a wide variety of objects, materials, parts, etc. The handling operations can be very simple and fuzzy or very complicated and precise. Robotic arms are the right tool to automate these operations and to facilitate the processes in almost of any area. At this stage, robotic arms, most of them known as manipulation robots, work successfully in many manufacturing areas. Usually, those areas are static and unchanging work environments, which allow the robotic arms to perform their operations according to advanced done programming.

The next stage challenge for the robotic arms is their capability to work in considerably cluttered and changing environments that can influence their proper functioning. Besides precise execution of the desired operations, the next stage robotic arms must ensure safety functioning within their working space. In cases of dynamic and cluttered environments, the robotics arms have to adapt to unknown in advance situations. The most important case to consider is ensuring a safety work—namely, avoidance of collisions and accidents with the surrounding objects.

The author's purpose of this paper is to begin a research on problems of safety functioning of autonomous robotic mechanisms in various working environments.

II. FUNCTIONAL DESCRIPTION OF COLLISION PREVENTION SYSTEM

The collision detection and prevention system consists of three modules that perform the following functions:

MODULE 1: "*Motion Control*"

This module implements the motion control according to set performance parameters. The motion control includes moving the arm end-effectors (EE) to desired positions of the working space and/or realization of desired trajectories of the arm.

MODULE 2:"*Detection of Obstacle and Distance Measurement*"

This module checks for presence of obstacles within the working area of the robotic arm and obtains the necessary measurements such as the global distance between the arm EE and an obstacle, as well as additional specific distance measurements, thus ensuring the complete measuremnet information for the safety work of the arm.

MODULE 3:"*Judgment for Situation and Decision for Action*

This module evaluates the working scene of the arm, estimates the degree of danger of the current situation and decides how to safely continue the current process. The possible decisions and actions are:

i. No danger situation and the motion can continue to the desired position or along the desired trajectory;

ii. Collision is possible – correction of the desired position or the desired trajectory;

iii. STOP - inevitable collision detected, impossibility to correct the motion, operator assistance required.

The block structure of the collision detection and prevention system is presented in Fig.1.

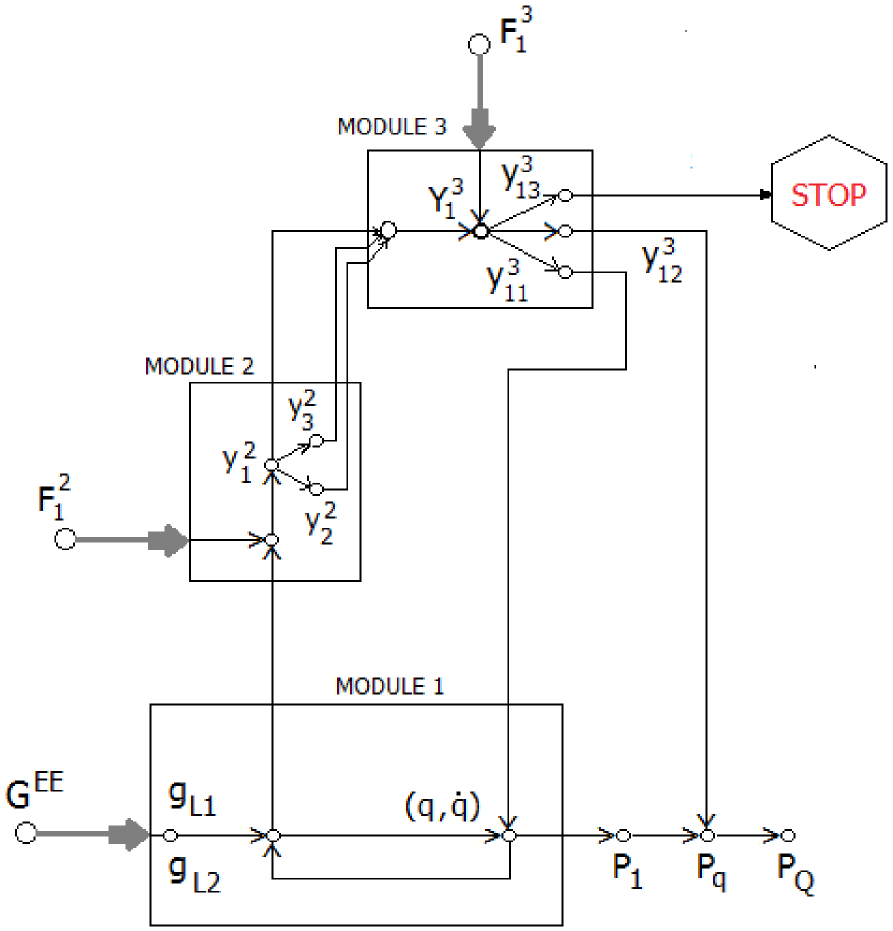

FIG 1. BLOCK STRUCTURE OF THE COLLISION PREVENTION SYSTEM

The system variables of the modules are described as follows:

$$
MODULE^{(1)} \left[\begin{array}{l}
\mathbf{G}^{EE} \text{ - set point for the arm end - effector(EE),} \\
\mathbf{g}_{L1}, \mathbf{g}_{L2} \text{ - set points for controller 1 and controller 2,} \\
(q_1(t), \dot{q}_1(t)) \text{ - link1 moves towards set point position } \mathbf{g}_{L1}, \\
(q_2(t), \dot{q}_2(t)) \text{ - link 2 moves towards set point position } \mathbf{g}_{L2}, \\
P_1^1, \ldots P_q^1, \ldots P_Q^1 \text{ - EE succesive possitions } P_q;
\end{array} \right.
$$

$$
MODULE^{(2)} \left[\begin{array}{l}
F_1^2 \text{ - check for presence of OBSTACLES,} \\
y_1^2 \text{ - } \mathit{glob\_dist}_{\mathrm{OBST}} \text{ measurement of global distance to OBSTACLE,} \\
y_2^2 \text{ - } \mathit{dist}_{L1\_obst} \text{ measurement of distance of link 1 to } \mathit{obstacle}, \\
y_3^2 \text{ - } \mathit{dist}_{L2\_obst} \text{ measurement of distance of link 2 to } \mathit{obstacle};
\end{array} \right.
$$

$$
MODULE^{(3)}\left[\begin{array}{l}
F_1^3 \equiv CC_{closnss} \text{ - criterion of closeness,} \\
Y_1^3 \text{ - evaluation -- } \left| glob\_dist_{OBST} - CC_{closnss} \right| \\
\text{- -- Decision for a degree of danger,} \\
y_{11}^3 \text{ --- no collision danger } \rightarrow \text{ continuation of motion,} \\
y_{12}^3 \text{ --- collision is possible} \rightarrow \text{ trajectory corection,} \\
y_{13}^3 \text{ --- STOP } \rightarrow \text{ impossible motion, necessity of operator's help;}
\end{array}\right.
$$

III. MATHEMATICAL BASIS

The dynamic model of n-dof robotic arm is well known as [1]:

$$\mathbf{D}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} = \boldsymbol{\tau} \tag{1}$$

Where $\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}, \ddot{\boldsymbol{\theta}}, \boldsymbol{\tau} \in R^n$ are n-vectors of joints position, velocity, acceleration and input driving torque, $\mathbf{D}(\boldsymbol{\theta}) \in R^{n\times n}$ matrix of inertia forces, $\mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) \in R^n$ matrix of centrifugal and coriolis forces?

The state vector $\mathbf{x}(t) \in R^{2n}$ consists of robotic arm joint angles and velocities $[\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}]$:

$$\mathbf{x}(t) = \left[\theta_1(t)\ \theta_2(t) \ldots \theta_n(t)\ \vdots\ \dot{\theta}_1(t)\ \dot{\theta}_2(t) \ldots \dot{\theta}_n(t)\right]^{\mathrm{T}}$$

The equation (1) is transformed in state space form:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(\mathrm{t}) + \mathbf{B}\mathbf{u}(\mathrm{t}) \tag{2}$$

where $\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} \mathbf{0} \\ -\mathbf{D}^{-1}(\boldsymbol{\theta})\,\mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) \end{bmatrix}$ and the control input is $\mathbf{u}(t) = \boldsymbol{\tau}(t)$.

A state space equation for a separate link i can be written as:

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{j=1,\, j\neq i}^{n} V_{ij} l_j(t) \tag{3}$$

with $x_i(0) = x_{i_0}, i = 1,2,...,\mathrm{n}$ as initial conditions for the links, and $l_j(t)$ - the closest distance between link j and detected obstacle, denoted as OBST, V_{ij}^{OBST} matrix of connections.

A. Free of Obstacle Control

Equation (2) is presented in discrete form as [2]:

$$\mathbf{x}_{k+1} = \mathbf{A}^*\mathbf{x}_k + \mathbf{B}^*\mathbf{u}_k \tag{4}$$

The matrixes $\mathbf{A}^*$ and $\mathbf{B}^*$ are calculated according to known formulas:

$$\mathbf{A}^* = \Phi(\mathrm{T}_0) = \mathrm{L}^{-1}\{[\mathrm{pI} - \mathbf{A}]^{-1}\}_{\mathrm{t}=\mathrm{T}_0}, \qquad \mathbf{B}^* = \mathrm{H}(\mathrm{T}_0) = \int_0^{\mathrm{T}_0} \Phi(\tau)\,\mathbf{B}\,d\tau \tag{5}$$

and T_0 is discretization interval for the system variables.

Closing the open system (4) by a feedback gain matrix $\mathbf{K} = [\mathrm{k1} \;\; \mathrm{k2}]$ and after some routine transformations, the state of the closed system becomes:

$$\mathbf{x}_{k+1} = [\mathbf{A}^* - \mathbf{B}^*\mathbf{K}]\mathbf{x}_k + \mathbf{B}^*\mathbf{u}_k^{\mathrm{G}} \tag{6}$$

The control input is calculated as [2]:

$$\mathbf{u}_k^{\mathrm{G}} = \mathbf{G}_k^{\mathrm{EE}} - \mathbf{K}\,\mathbf{x}_k \tag{7}$$

where $\mathbf{u}_k^{\mathrm{G}}$ is the control input that ensures free movement of the arm end-effectors (EE) to the desired position when no obstacles exist within the working space of the robotic arm.

B. Obstacle consideration and motion correction

The closed system is described, after taking into account obstacle existence, as:

$$\mathbf{x}_{k+1} = [\mathbf{A}^* - \mathbf{B}^*\mathbf{K}]\mathbf{x}_k + \mathbf{B}^*\mathbf{G}_k^{\mathrm{EE}} + \mathbf{F}^* Z_k^{obst} \tag{8}$$

The control input contains a second component $\mathbf{u}_k^{obst}$:

$$\mathbf{u}_k = \mathbf{u}_k^{\mathrm{G}} + \mathbf{u}_k^{obst} \tag{9}$$

where $\mathbf{F}(\mathrm{T}_0) = \int_0^{\mathrm{T}_0} \mathbf{\Phi}(\tau)\,\mathbf{C}\,d\tau = \mathbf{F}^*$ and $\mathbf{u}_k^{obst}$ is the component of the control vector that realizes trajectory correction after considering existence of obstacle around the EE or the link j.

Combining (7), (8) and (9) one can get the model:

$$\mathbf{x}_{k+1} = \mathbf{A}^*\mathbf{x}_k + \mathbf{B}^*\mathbf{K}\mathbf{u}_k^{\mathrm{G}} + \mathbf{B}^*\mathbf{u}_k^{Z} + \mathbf{F}^*\mathbf{z}_k \tag{10}$$

The following relation is considered for the purpose of control correction as a result of existence of potential collision for link j and an obstacle, detected in the near closeness:

$$\mathbf{B}^* u_{j,k}^{Z} + \mathbf{F}^* z_{j,k} = l_{j,k} \tag{11}$$

where $l_{j,k}$ is the closest measured distance between the link j and the obstacle. Based on the above equation it is calculated:

$$u_{j,k}^{Z} = (-\mathbf{B}^*)^{-1}\mathbf{F}^*\mathbf{z}_k + (\mathbf{B}^*)^{-1} l_{j,k} \tag{12}$$

where $u_{j,k}^{Z}$ is the control input to correct the motion because of obstacle presence near link j.

IV. BASIC SIMULATIONS FOR 2 DOF PLANAR ROBOTIC ARM

The results from a computer program simulation are shown in Fig. 2(a,b,c,d) [3].

Fig.2a shows a potential collision situation. The second link is very close to the obstacle.

Fig.2b shows collision occurrence, when the second link crashes the obstacle.

Fig. 2c shows obstacle avoidance from the robotic arm end-effectors.

Fig.2d shows collision-free motion after the collision avoidance.

Potential Collision **Collision Occurrence** **Collision Avoidance**

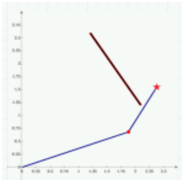

Fig. 2a

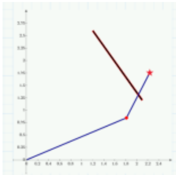

Fig.2b

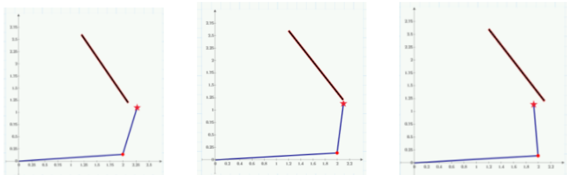

Fig.2c

Collision-Free Motion

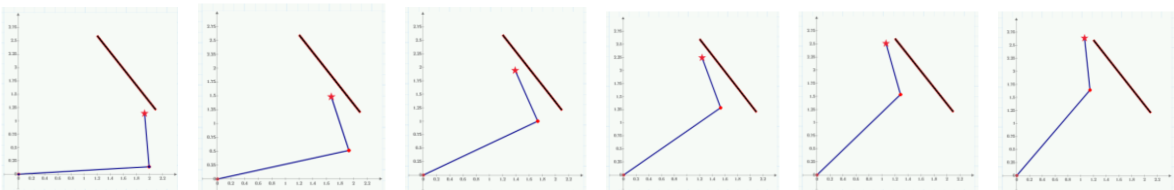

Fig. 2d

V. CONCLUSION

A generic functional model for collision avoidance and collision free-motion of robotic arms is proposed. Basic simulation result for two dof planar robotic arm is presented. Further detailization of research is under planning.

REFERENCES

[1] M. W. Spong, S. Hutchinson, and M. Vidyasagar, “Robot Modeling and Control”, by John Wiley & Sons, 2006.

[2] K. Ogata,“System Dynamics,” 4th Edition, Pearson Education, Inc., 2004.

[3] G.V.Tzvetkova, “Network Modeling of System Goals Attainment”, Proceedings for the 3rd International Innovations and Real-Time Applications of Distributed Sensor Networks Symposium., Shreveport Convention Center, Shreveport, Louisiana, USA, November 26-27, 2007.