SOME CONSIDERATION REGARDING MOTION CONTROL AND PLANNING

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Abstract: This paper presents a method to find energy-efficient motion path planning avoiding obstacles and obeying constraints. To allow for real-time computation, like human strategy, a path is not completely planned before motion. A motion planning module establish the intermediate positions and velocities points of moving object between starting and goal position. A new segment of total path is computed at each time step between each intermediate points, over a limited horizon. The control signals for torque, speed and position calculated between two states of a planar mechanism are applied in a feed-forward manner to motors drive controllers. There are several experimental results, which confirm the specified performances of the motion control system.

Keywords: Optimal path planning, Trajectory optimisation, Fixed arrival time, Feed-forward control, PM synchronous motor drive

INTRODUCTION

The basic problem discussed in this paper is that of calculating an optimal path between two states of a mobile robot or a planar mechanism, used for examples in industrial manufacturing application. The controls on the mobile robot are its shaft torque and steering angle (the angle the front wheels make with car's long axis). The controls of the planar mechanism are the torque of both permanent magnet (PM) synchronous motors for x, y displacements.

In the following we consider a planar xy mechanism with two PM servomotors. Our task is to validate point-to-point motion manager, which execute the path planning. We shall use a rigid body second-order dynamics model (double integral) with servo feedback design. We shall also validate the controller design with feed-forward command using the detailed analysis model. The path planning and feed forward modules will plan the motion path and compute feed forward. It will continuous provide the reference input to the PM servo system. Our control algorithm performs a smooth path planning based on the motion intermediate points obtained from manager module connected to the user input. The user input consists in a processing sequence task, which establishes the motion intermediate points in aim to avoid the obstacles and to accomplish dynamic performances.

Previous works

Energy conservation of autonomous vehicles can be achieved in several ways. The first step in doing is to use energy efficient motors. After the motor is chosen, optimal path planning can save energy. The path-planning problem consists of finding a collision free path of configuration. Mall and Kavraki [9] presented a new path planning technique for a flexible robot, using the minimal strain curves. Finding a smooth curve that satisfies end point constraints is difficult and finds minimal energy curves' using a finite element method is even more challenging. The energy is the integral of the curvature squared plus the torsion squared-over the entire length of the curve. The curvature and torsion

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are numerically computed for n points along the curve and minimizes the energy of resulting curves.

Recently developed approach to optimal path planning of autonomous vehicles to account for safety is presented in [2]. Recent research in the field of trajectory optimization for Unmanned Aerial Vehicles (UAV's) is based on the use of mixed integer linear programming (MILP) to account for obstacles and collision avoidance constraints. The approach that allows for real-time path planning is a receding horizon strategy in which a new segment of the total path is computed at each time step by solving a MILP over a limited horizon.

1. *Problem formulation*

Let Ọ be a single rigid object drived by an autonomous electric system, moving in a Euclidian space, called workspace, represented as R^N, with N=2 or 3.

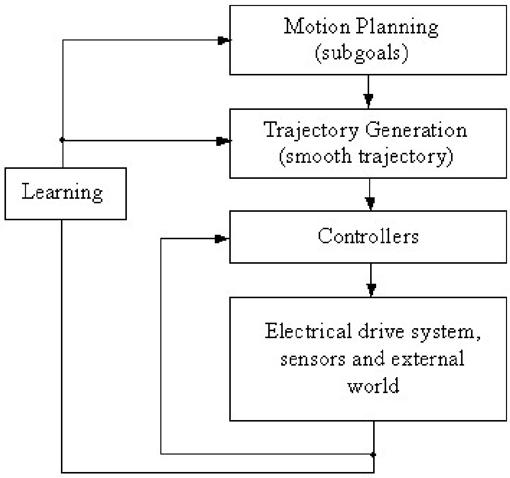

Fig.1 General schema of a motion control and planning

Let ß$_1$…ß$_q$ be fixed objects distributed in R^N. The ß is are called obstacles.

Assume that both the geometries of Ọ, ß1…ß$_q$ and the locations of the ßi's in R^N are accurately known.

Assume further that no kinematics constraints limit the motions of Ọ so we say that Ọ is a free – flying object.

The basic problem discussed in this paper is: given an initial position and a goal position of Ọ in R^N, generate a path specifying a continuous sequence of positions of Ọ avoiding contact with the ß$_i$'s, starting at the initial position and terminating at the goal position. The general structure of motion system and planning is represented in figure 1.

The motion planning module establish the intermediate positions and velocities points of moving object between starting and goal position, avoiding obstacles and obeying constraints.

The trajectory generation module calculate the control laws for torque, speed and position controllers in feed-forward manner between intermediate points given by the motion planning module.

There are different objectives (performances index's) in finding optimal paths (N=2).

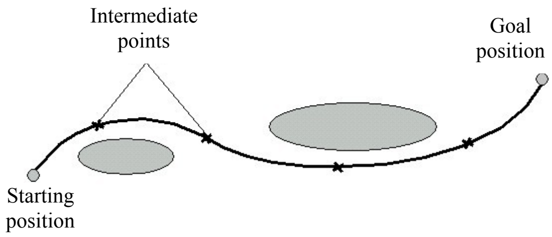

Fig.2 Trajectory generation by intermediate points avoiding obstacles

- Minimum square-velocity (shortest distance)

$$(1)\quad \min\int_0^T \frac{1}{2}[(\frac{dx}{dt})^2+(\frac{dy}{dt})^2]dt$$

- Minimum acceleration

$$(2)\quad \min\int_0^T \frac{1}{2}[(\frac{d^2x}{dt^2})^2+(\frac{d^2y}{dt^2})^2]dt$$

- Minimum jerk

$$(3)\quad \min\int_0^T \frac{1}{2}[(\frac{d^3x}{dt^3})^2+(\frac{d^3y}{dt^3})^2]dt$$

- Minimum time

$$(4)\quad \min\int_0^T dt$$

We can utilize Hamilton or Lagrange equations of motion for finding the optimal path with the minimum square –velocity performances index (shortest distance).

$$(5)\quad \min\int_0^T f(x,\dot{x},y,\dot{y},t)dt$$

the Euler – Lagrange equations are

$$(6)\quad \frac{d}{dt}(\frac{\partial f}{\partial \dot{x}})-\frac{\partial f}{\partial x}=0 \qquad \frac{d}{dt}(\frac{\partial f}{\partial \dot{y}})-\frac{\partial f}{\partial y}=0$$

When the performances index is minimum acceleration

$$(7)\quad \min\int_0^T f(x,\dot{x},\ddot{x},y,\dot{y},\ddot{y},t)dt$$

The Euler-Lagrange equation or

$$(8)\quad \frac{d^2}{dt^2}(\frac{\partial f}{\partial \ddot{x}})-\frac{d}{dt}(\frac{\partial f}{\partial \dot{x}})+\frac{\partial f}{\partial x}=0$$

$$(9)\quad \frac{d^2}{dt^2}(\frac{\partial f}{\partial \ddot{y}})-\frac{d}{dt}(\frac{\partial f}{\partial \dot{y}})+\frac{\partial f}{\partial y}=0$$

with the initial and final condition:

$x(0)=x_0 \quad y(0)=y_0 \quad \dot{x}(0)=v_{x0} \quad \dot{y}(0)=v_{y0}$

$$x(T)=x_T \quad y(T)=y_T \quad \dot{x}(T)=v_{xT} \quad \dot{y}(T)=v_{yT}$$

We consider a planar xy positioning mechanism with two permanent magnet (PM) synchronous motors. Is quiet direct to demonstrate that minimum acceleration performances index represents the minimum energy control.

$$(10) \quad \min \int_0^T (R_x i_x^2 + R_y i_y^2) dt$$

where R_x, R_y are the PM synchronous motor resistances and respectively i_x and i_y the motor currents.

2. *Finding the motion control laws*

The basic problem discussed in this paper is that of calculating an optimal smooth path between two states of an autonomous planar motion mechanism, while avoiding obstacles and obeying constraints. The discussion here is restricted to the case of minimal energy planning, as this leads to a straight-forward linear control laws for torque command which was formulated in [7]. The most direct application is to use a fixed arrival time, which means that the arrival time between two intermediate trajectory points is specified. The mathematical model is solved over a limited horizon in which a new segment of the total path is computed at each time step. Lets be the intermediate k state with ω_{xk}, ω_{yk}, speed components and α_{xk}, α_{yk} position components. The planar mechanism is drived by two motor one for each x, y axis. The minimal energy control law was presented in [6]

$$(11) \quad m_{ki} = -\frac{m_{dki}}{t_{ki}}\tau + m_{dki} + m_{Lki} \qquad i = x, y$$

where

- m_{kx} , m_{ky} are the torques which can transfer the mechanism from initial state k to the final state k+1 with fixed arrival time t_{fk}
- m_{Lki} are the load torques of motion on the x,y axis.
- m_{dki} are the initial motion dynamical torques.
- τ is time between ω_{ki} and $\omega_{k+1,i}$;

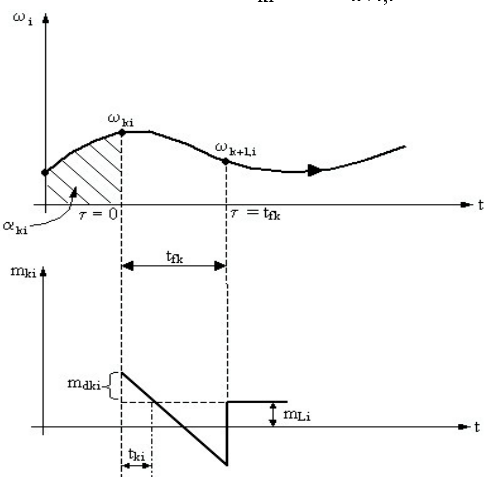

Fig.3 Planning the speed and torque trajectories

The motion equations are:

$$(12) \quad J\dot{\omega}_i = -\frac{m_{dki}}{t_{ki}}\tau + m_{dki} \qquad i = x, y$$

The initial and final speed conditions are:

$$\tau = 0 \qquad \omega_i = \omega_{ki}$$
$$\tau = t_{fk} \qquad \omega_i = \omega_{k+1,i}$$

From (12) results

$$(13) \quad J(\omega_{k+1,i} - \omega_{ki}) = -\frac{m_{dki}}{t_{ki}} \cdot \frac{t_{fk}^2}{2} + m_{dki} t_{fk}$$

The initial and final position conditions are:

$$\tau = 0 \qquad \alpha_i = \alpha_{ki}$$
$$\tau = t_{fk} \qquad \alpha_i = \alpha_{k+1,i}$$

From (12) results

$$(14) \quad J(\alpha_{k+1,i} - \alpha_{ki}) = -\frac{m_{dki}}{t_{ki}} \cdot \frac{t_{fk}^3}{6} + m_{dki}\frac{t_{fk}^2}{2} + J\omega_{ki} t_{fk}$$

From (13) and (14) results:

$$(15) \quad m_{dki} = 6J\frac{\alpha_{k+1,i} - \alpha_{ki}}{t_{fk}^2} - 2J\frac{\omega_{k+1,i}}{t_{fk}} - 4J\frac{\omega_{k,i}}{t_{fk}}$$

$$(16) \quad t_{ki} = \frac{-\dfrac{m_{dki} \cdot t_{fk}^2}{2}}{J(\omega_{k+1,i} - \omega_{ki}) - m_{dki} t_{fk}}$$

The equations (15) and (16) determine completely the torque command (11) which transfer the mobile from the state k to state k+1 with minimum energy cost, that means the minimum acceleration performance index (2) if the load torque m_{Lki} is known.

3. *Tuning the controllers for drive system*

The optimal trajectories computed by trajectories generation model represent the feed-forward reference signals for torque, velocity and position controllers. The drive trajectories follow the computed trajectories with a precision obtained by corresponding tuning of the controllers.
This precision improves if estimates of the load torque are available.

The simplified diagram block of the motion system with synchronous machine is given in the figure 4.
The closed loop control of permanent magnets (PM) synchronous machine has three main objectives: to control the $\mathbf{i_d}$ current component near zero, to control the torque by $\mathbf{u_q}$ voltage component and to control the machine speed and position by imposing the appropriate torque. Flux, torque, speed and position controllers accomplish these conditions.

The two control channels for torque and flux are coupled by product nonlinearities of machine equations.

The general equation of the stator armature for permanent magnets (PM) synchronous motor is

$$(17)\quad u = Ri + j\omega_1\varphi + \frac{d\varphi}{dt}$$

All the quantities are expressed as complex phasors in a (d,q) coordinate system. Direct and quadrature components of stator flux φ are:

$$(18)\quad \begin{aligned}\varphi_d &= L_d i_d + \Phi_0\\ \varphi_q &= L_q i_q\end{aligned}$$

with Φ_0 as PM flux.

From (17, 18) results:

$$(19)\quad T_d\frac{di_d}{dt} + i_d = \frac{u_d}{R} + \omega_1 T_q i_q$$

$$(20)\quad T_q\frac{di_q}{dt} + i_q = \frac{u_q}{R} - \omega_1 T_d i_d - \omega_1\frac{\Phi_0}{R}$$

The nonlinear parts of equations (19, 20) are:

$$f_d = \omega_1 T_q i_q \quad f_q = \omega_1 T_d i_d + \frac{\omega_1}{R}\Phi_0$$

The torque and flux controllers generate the i_q^* and i_d^* controls for torque and flux (fig.5). Because the inverter that supply the motor is voltage controlled, it must determine the relations between the current controls i_d^*, i_q^* and the corresponding voltage controls u_d^*, u_q^*. That is made by inverse model, which results from equations:

$$(21)\quad T_d\frac{di_d}{dt} + i_d = \frac{u_d}{R} + f_d$$

$$(22)\quad T_q\frac{di_q}{dt} + i_q = \frac{u_q}{R} + f_q$$

From figure 5 we obtain, based on the inverse machine model, the linear part of the torque and flux controllers:

$$(24)\quad H_q(s) = \frac{R(1+sT_q)}{\tau_q s} \quad (23)\quad H_d(s) = \frac{R(1+sT_d)}{\tau_d s}$$

Designing the controllers is quite direct. The inverter with its driver circuits introduces an equivalent mean delay T_μ. The response time of the torque and flux control loops depends on the inverter mean delay T_μ. When applying the classical rules for the symmetrical optimum, the open loop cross over angular frequency is:

$$(25)\quad \omega_{cross} = \frac{1}{2T_\mu}$$

For torque controller the open loop gain is

$$(26)\quad V_q = \frac{K_m}{\tau_q} = \omega_{cross}$$

where K_m is the torque coefficient.

$$(27)\quad K_m = K_1[(L_d - L_q)i_d + \Phi_0]$$

The τ_q parameter is

$$(28)\quad \tau_q = 2T_\mu K_m$$

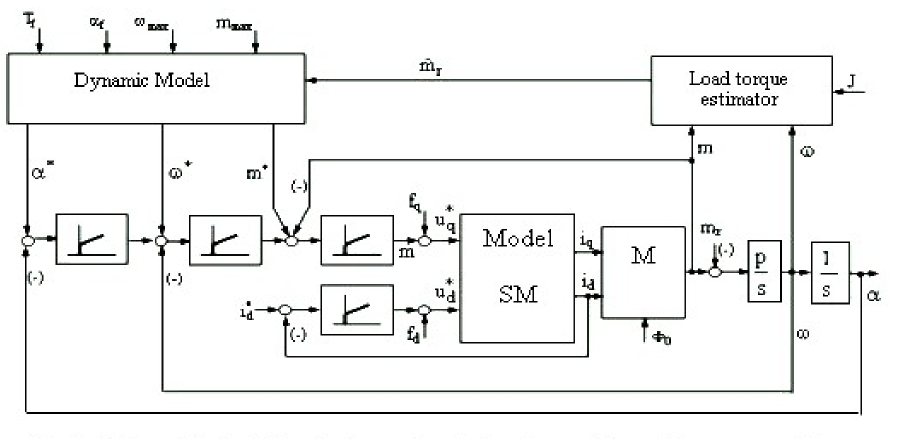

Fig. 4 Schema block of the electromechanical system with synchronous machine (PM)

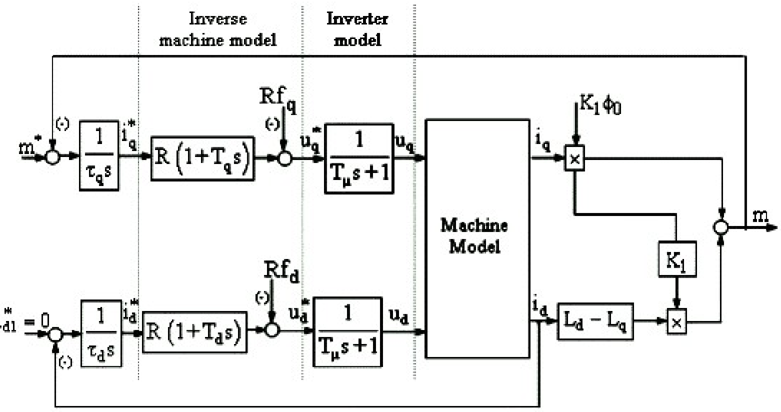

Fig.5 Decoupling synchronous machine mathematical model

4. EXPERIMENTAL RESULTS

A C++/Matlab simulation programs the two PM synchronous motors, which drives the mobile xy mechanism. The first test was referred at tracking a sinusoidal trajectory by imposing some intermediate trajectory points. The second test was referred at a trajectory, which must avoid the obstacles. The planning module sketched the desired trajectories by any intermediate points in aim to avoid obstacles.

Sinusoidal motion planning by five intermediate points is illustrated in table 1.

Table1

t_{kx} [s]	$\alpha_{kx} \to \alpha_{k+1,x}$ [rad]	$\omega_{kx} \to \omega_{k+1,x}$ [rad/s]	$\alpha_{ky} \to \alpha_{k+1,y}$ [rad]	$\omega_{ky} \to \omega_{k+1,y}$ [rad/s]	t_{ky} [s]
1/7	$0 \to \alpha_{max}$	$0 \to 0$	$\alpha_{max} \to -\alpha_{max}$	$0 \to 0$	2/7
2/7	$\alpha_{max} \to -\alpha_{max}$	$0 \to 0$	$-\alpha_{max} \to \alpha_{max}$	$0 \to 0$	2/7
2/7	$-\alpha_{max} \to \alpha_{max}$	$0 \to 0$	$\alpha_{max} \to -\alpha_{max}$	$0 \to 0$	2/7
2/7	$\alpha_{max} \to -\alpha_{max}$	$0 \to 0$	$-\alpha_{max} \to 0$	$0 \to 0$	1/7

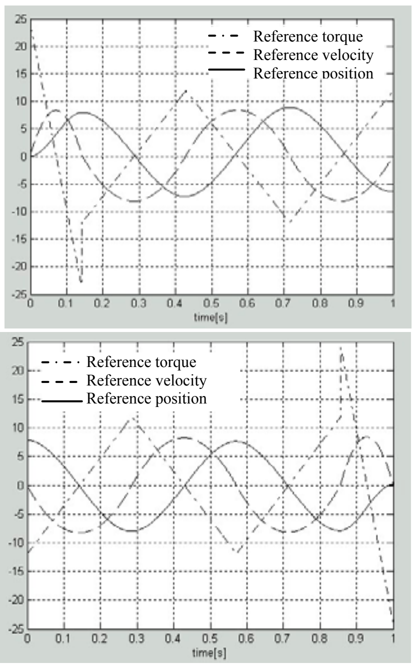

Fig.6 a, b. The smooth trajectories generated starting from the five intermediate points (table1)

The smooth torque command velocity and position trajectories (feed-forward reference for PM synchronous motor), generated by trajectory generation module are illustrated in figures 6a, 6b.

In figure 7 was represented the PM synchronous motor drive system dynamical responses when the feed-forward references was the smooth trajectories generated by five intermediate points (fig.6a, 6b).

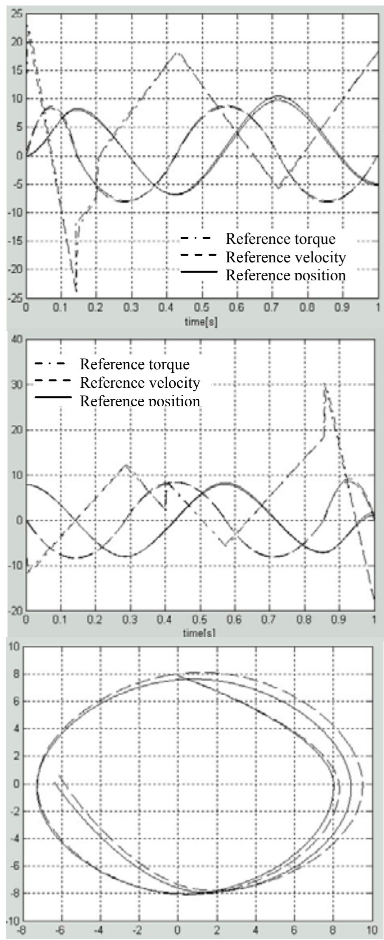

Fig.7a, b, c, where:

- a-represent movement on axis X of the planar mechanism;
- b-represent movement on axis Y of the planar mechanism
- c-movement on axis XY of the planar mechanism

In the following we consider the working environment of a xy planar mechanism. The horizontal axis is considered as x-axis. Based on the starting and goal destination the motion-planning module establishes the intermediate points of trajectory, avoiding obstacles. Let be five intermediate points (figure 8). In table 2 are specified the data obtained from trajectory planning module. Based on this data, the trajectories generation module computes the feed-forward references for torque, speed and position controllers.

Table2. The data corresponding to intermediate points in the working environment represented in figure 8

t [s]	t_{fk} [s]	om_{1x} [rad/s]	om_{2x} [rad/s]	alf_{1x} [rad]	alf_{2x} [rad]	om_{1y} [rad/s]	om_{2y} [rad/s]	alf_{1y} [rad]	alf_{2y} [rad]
0.5	0.5	0	14π	0	$3{,}5\pi$	0	0	0	0
0.8	0.3	14π	0	$3{,}5\pi$	$4{,}5\pi$	0	5π	0	$0{,}75\pi$
1.1	0.3	0	0	0	0	5π	5π	$0{,}75\pi$	3π
1.6	0.5	0	5π	0	π	5π	0	3π	5π
1.9	0.3	5π	0	π	4π	0	0	0	0

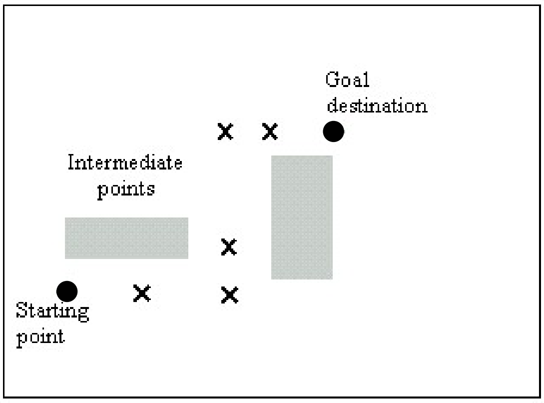

Fig.8 The environment and the distribution of the starting, intermediate and goal points

In figure 9 is represented the trajectories of the mechanism in the working environment.

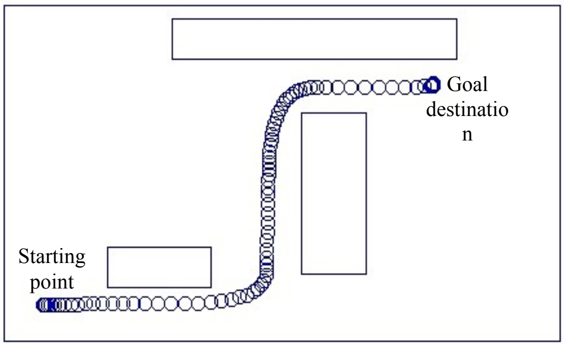

Fig.9 A planning horizon of motion in a safe trajectory to the goal

5. CONCLUSIONS AND FUTURE WORK

In this paper a free-collision, real-time path planning algorithm for a planar mechanism was presented.
The method was illustrated by two examples: one in which a sinusoidal trajectory was tracking by imposing any intermediate position and velocities points, a second in which the planar mechanism must avoid the obstacles considering five intermediate trajectory points. Based on this data the trajectories generation module computes the feed-forward references for torque, speed and position controllers, optimising the energy control.
Future work will concentrate on extending the planning algorithm for autonomous vehicles in the case of fuel-optimal planning with fixed arrival time. Note than the robustness of the technique with respect to uncertainties in the dynamics and disturbances in the environment is based on the on line load torque estimation.

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