Control Strategies for Robotic Manipulators

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***Abstract*—This survey is aimed at presenting the major robust control strategies for rigid robot manipulators. The techniques discussed are feedback linearization/Computed torque control, Variable structure compensator, Passivity based approach and Disturbance observer based control. The first one is based on complete dynamic model of a robot. It results in simple linear control which offers guaranteed stability. Variable structure compensator uses a switching/relay action to overcome dynamic uncertainties and disturbances. Passivity based controller make use of passive structure of a robot. If passivity of a feedback system is proved, nonlinearities and uncertainties will not affect the stability. Disturbance observer based controllers estimate disturbances, which can be cancelled out to achieve a nominal model, for which a simple controller can then be designed. This paper, after explaining each control strategy in detail, finally compares these strategies for their pros and cons. Possible solutions to cope with the drawbacks have also been presented in tabular form.**

Index Terms*— *Robot control, Control strategies, Robot manipulators.

I. INTRODUCTION

There are basically two philosophies for controlling a robot having nonlinear and an uncertain behavior. One is adaptive and the other is robust control. In a properly designed adaptive control, the controller tries to 'learn' the uncertain parameters of the system and achieves the best performance. On the other hand, robust controllers are fixed structure that guarantees stability and performance in bounded uncertainties. In this paper, a survey of four robust control techniques for controlling the motion of a rigid robot is presented. These are Feedback Linearization/Computed Torque Control (CTC), Variable Structure Compensator (VSC), Passivity Based Control (PBC) and Disturbance Observer Based Control (DOBC) approaches.

Feedback linearization is based on linearizing the nonlinear dynamics of a robot manipulator, when the values of parameters along with online measurements of the states are available. It is useful due to the availability of large number of linear techniques applicable for linear systems. CTC is a special feedback linearization method that leads to LTI closed loop system with Global Asymptotic Stability (GAS) if controller gains are constant, symmetric and positive definite.

The second strategy, VSC uses the nonlinear feedback to control an uncertain system providing stability with modeling imprecision and uncertainties. The idea is to drive the error to a switching surface which has invariance to modeling uncertainties and external disturbances. VSC has two phases: First is reaching phase that uses inverse dynamics to model uncertainties. The second is the sliding mode, which has discontinuity and uses high control gain to overcome uncertainties and disturbances. The third control technique, PBC is based on the physically passive structure of robot system. This method maintains the passivity of feedback system, which has guaranteed stability despite of uncertainties in parameters and nonlinearities. Advantage of passivity based adaptive controllers over linearization is that the estimate of the inertia matrix inversion is not needed and also no joint acceleration measurements are required. The last strategy for controlling a robotic manipulator, discussed in the present survey is DOBC that is designed to estimate the sum of the disturbance torques by computing the difference between the output of the nominal model and actual output which is the equivalent disturbance applied to the nominal model. For a multi-link robotic system, the DOBC considers the coupling torques from other links as an unknown external torque, so independent joint control is possible. Hence, a simple controller can be designed for the independent nominal model.

Earliest surveys on rigid robot manipulators reported in the literature were presented by Abdallah et al. [1] and Sage et al. [2], the later one in late 90s. To the knowledge of authors, scientific community has not reported latest state-of-the-art review about the control strategies of rigid bodies during the last decade. Various later techniques e.g. DOBC have not been discussed in the past reviews.

The paper is organized as follows: Section II presents robot dynamics equations, section III discusses feedback linearization/CTC scheme while Section IV reviews VSC scheme. PBC and DOBC are explained in Section V and VI respectively. Finally Section VII comments on conclusion and presents a tabular comparison of the control strategies discussed.

II. ROBOT DYNAMICS

The Euler Lagrange equation for the dynamics of an n serial link robotic manipulator with revolute joints is given by

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f(\dot{q}) = \tau \quad (1)$$

Where $M(q)$ is a nxn inertia matrix, $C(q,\dot{q})$, $g(q)$ and $f(\dot{q})$ are nx1 vectors of Coriolis centrifugal forces, gravitational and frictional forces respectively. τ is the nx1 vector applied to the joints of the robot and q, $\dot{q}$ and $\ddot{q}$ are angular position, velocity and acceleration respectively. Relevant properties are mentioned below:

1. Inertia matrix must be bounded and positive.
2. Parameter linearity: dynamic equation can be written as

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f = \tau = Y(q,\dot{q},\ddot{q})\theta \quad (2)$$

Where θ denotes unknown parameter matrix and $Y(q,\dot{q},\ddot{q})$ called regressor denotes known parameters.

3. Skew symmetric property:

$$q^T[\dot{M}(q) - 2C(q,\dot{q})]q = 0 \qquad \forall q \neq 0 \quad (3)$$

W. Spong [3] used the skew symmetry property of dynamic equation and parameter linearity of robot dynamics. Tracking error ultimate boundedness is dependant only on inertia parameter of the robot. It is applicable where uncertainties are not too large and the main concern is robustness to disturbances and un-modeled dynamics.

III. FEEDBACK LINEARIZATION

This method uses nonlinear feedback to cancel nonlinearities of robot dynamics so that the overall closed loop system behaves like a linear system. The inverse dynamics is used for this purpose and to decouple robot's equation. It has guaranteed stability of a closed loop system.

The error in trajectory tracking can be written as [1]

$$e = q - q_d \quad (4)$$

Using feedback linearization or multi variable approach, one is able to linearize the nonlinear robot system to

$$\dot{e} = Ae + Bv \quad (5)$$

Where

$$A = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ I \end{bmatrix}$$

$$e = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$$

$$v = D(q)^{-1}[\tau - h(q,\dot{q})] - \ddot{q}_d \quad (6)$$

Where $D(q)$ is an inertia matrix and $h(q,\dot{q})$ represents nx1 vector of Coriolis, Centrifugal and Gravity terms. The problem is reduced to find a linear control system (v) which will give the desired closed loop performance (i.e. computing F, G, H and J) as in

$$\dot{z} = Fz + Ge \quad (7)$$

$$v = Hz + Je \quad (8)$$

$$v(t) = [(sI - F)^{-1} G + J]e(t) \equiv C(s)e(t) \quad (9)$$

Which gives output $v(t)$ of a system $C(q)$ with input $e(t)$. Defining following parameter, a nonlinear control equation is obtained.

$$\tau = D(q)[\ddot{q}_d + v] + h(q,\dot{q}) \quad (10)$$

Since D and h hold uncertain values, so estimates are used in the control law.

$$\tau = \hat{D}[\ddot{q}_d + v] + \hat{h} \quad (11)$$

Control diagram is shown in Fig. 1.

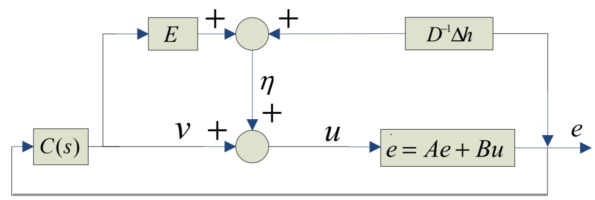

Figure 1. Linear multi variable design

Considering disturbances, the corresponding equations can be written as

$$\dot{e} = Ae + B(v + \eta) \quad (12)$$

$$\eta = E(v + \ddot{q}_d) + D^{-1}\Delta h \quad (13)$$

$$E = D^{-1}\hat{D} - I_n \quad (14)$$

$$\Delta h = \hat{h} - h \quad (15)$$

η is nonlinear function of e and v, representing disturbances. These may be due to modeling uncertainties, external disturbances or noisy measurements. So this approach is employed for designing a linear closed loop controller *C(s)*, which may be stable in some sense.

Zhihong et al. [4] assumes a partially known system, linearization approach with nominal feedback is used to asymptotically track the desired trajectory and VSC is designed to eliminate error due to unknown portion of system. Majid et al. [5] proposed a less complex control based on approximate feedback linearization method. Exact linearization has been used for an approximate imaginary robot with an inertia matrix having zero Riemannian curvature. System parameters have been selected based on optimal least square method to reduce tracking error.

A special application of feedback linearization is CTC, which has two loops. The inner loop is for nonlinearity compensation and the outer loop is for prescribed trajectory tracking, which may be any combination of the Proportional, Integral and Derivative terms. Below is the block diagram of CTC with PD feedback [6].

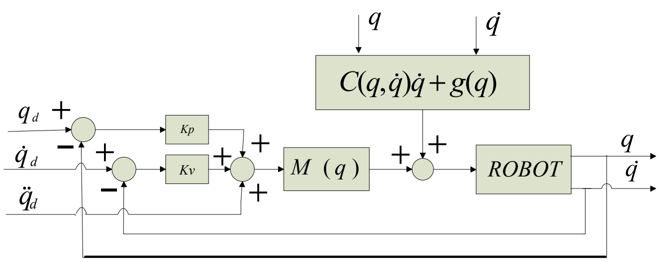

Figure 2. Block diagram of computed torque control

Corresponding control law with PD control is given by

$$\tau = M(q)(\ddot{q}_d - u) + C(q,\dot{q})\dot{q} + g(q) \tag{16}$$

Where

$$u = -K_v\dot{e} - K_p e \tag{17}$$

is an auxiliary control signal. The closed loop error dynamics is

$$\ddot{e} + K_v\dot{e} + K_p e = 0 \tag{18}$$

In state space form, it can be written as

$$\begin{bmatrix}\dot{e}\\ \ddot{e}\end{bmatrix} = \begin{bmatrix}0 & I\\ -K_p & -K_v\end{bmatrix}\begin{bmatrix}e\\ \dot{e}\end{bmatrix} = A\begin{bmatrix}e\\ \dot{e}\end{bmatrix} \tag{19}$$

This is a linear error dynamics and its solution is used to access the stability of origin.

CTC requires exact knowledge of dynamics model parameters, which are rarely known in priori. A CTC with compensation has been introduced by Kelly et al. [7] to compensate for modeling errors. The gain can't be kept fixed due to uncertainties in parameters. Accordingly the gain of controller must be modified in a nonlinear manner to compensate for disturbances and uncertainties in real applications. In [8] nonlinear gain matrices have been determined using Fuzzy Logic, avoiding torque saturation and compensate error due to friction. GAS is guaranteed if fuzzy set output variables are strictly positive. Song et al. [9] have divided robot dynamics into two parts. The control input for both parts is

$$\tau = \tau_0 + \tau_c \tag{20}$$

Where τ_0 is control input for nominal system with known parameters for first part (CTC is used for this part). τ_c is the compensating torque for the second part to compensate the unknown lump uncertainties. Fuzzy compensator update is done using Lyapunov stability theorem.

Paccot et al. [10] have proved that a vision based CTC for parallel robot is less sensitive to mechanical identification than a classical controller. Comparison of the proposed scheme with Cartesian space CTC having forward kinematic models to prove its validity. If exact values of all parameters in robot dynamics are known, a feedforward term will largely compensate for nonlinearities and will calculate input joint torque. The feedback term is used for stability. In case of uncertainties, high feedback gains are used to counteract the effects of uncertainties, which may create problems like torque saturation, large energy consumption etc. To avoid high feedback gains, exact values of dynamic parameters are required for feedforward terms, resulting in a regression problem. Tuong et al. [11] have used Local Weighted Projection Regression (LWPR) for its low computational cost with Gaussian Progress Regression (GPR) due to its high learning accuracy and less tuning requirement properties. Experiments on 7-DOF robots have been performed for proposed Local Gaussian Process Regression (LGP), GPR, and v-SVR (Support Vector Regression) to show its superiority.

The linear feedback systems can't achieve fast response without overshoot. Furthermore nonlinearities due to actuator saturation and friction can deteriorate performance and create position errors. To achieve fast transient response while compensating friction and nonlinearities, Peng et al. [12] have combined CTC with Composite Nonlinear Feedback (CNF). CNF introduced another saturation term, which avoids actuator saturation and utilizes full actuator capability. The CTC/CNF parameters are tuned to eliminate the effects of friction. Also the CNF ensures stability. Choi et al. [13] have used a model of robot dynamics in parallel with the plant to eliminate disturbances and modeling uncertainties. The stability of the scheme is proved using Lyapunov direct method for positioning problems.

IV. VARIABLE STRUCTURE COMPENSATOR

VSC (also named as Sliding Mode Controller SMC) is used for many nonlinear structure controls. Its main feature is to drive the error to a switching surface, after which the system functions in the sliding mode and has invariance to modeling uncertainties and disturbances. Two main drawbacks of VSC are chattering phenomenon due to discontinuity and lack of robustness in reaching phase. To overcome these drawbacks several methods are proposed including intelligent control approaches, which include Fuzzy logic control and Neural Network (NN) control.

VSC is combined with PD or PID to achieve tracking control of robots using suitable input torque. The error is the difference between the desired trajectory (q_d) and position vector (q). Defining a sliding surface for PID control

$$s = \dot{e} + \lambda_1 e + \lambda_2 \int_0^t e dt \tag{21}$$

So $s = 0$ is a stable sliding surface if $e \rightarrow 0$ as $t \rightarrow \infty$. Based on sliding surface, the dynamic equation can be written as

$$M\dot{s} = -Cs + f + \tau_d - \tau \tag{22}$$

Where

$$f = M(\ddot{q}_d + \lambda_1 \dot{e} + \lambda_2 e) + C\left(\dot{q}_d + \lambda_1 e + \lambda_2 \int_0^t e dt\right) + G \tag{23}$$

Corresponding control input is

$$\tau = \hat{f} + K_v s + K \mathrm{sgn}(s) \tag{24}$$

and the outer PID loop is

$$K_v s = K_v \dot{e} + K_v \lambda e + K_v \lambda \int_0^t e dt \tag{25}$$

In order for the system state to reach sliding surface (s=0) in a limited time, the controller must satisfy the following condition

$$\frac{1}{2}\frac{d}{dt}[s^T Ms] < -\eta \, (s^T s)^{1/2} \quad \eta > 0 \tag{26}$$

Zhihong at al. [4] considers the dynamics as partially known. For such a system, feedback linearization is used with a nominal controller to track the desired trajectory. VSC is designed to eliminate uncertainties and disturbances. But to compensate for chattering effect, boundary layer compensator is used, in which saturation function is used instead of sgn function in the discontinuous part of control.

$$\mathrm{sat}\left[\frac{s}{\varphi}\right] = \begin{cases} 1 & s \geq \varphi \\ \dfrac{s}{\varphi} & -K < s < \varphi \\ -1 & s \leq \varphi \end{cases} \tag{27}$$

There is a boundary layer around the sliding surface. Once the state trajectory reaches this layer it will stay there.

Choi [14] has proposed a method to eliminate chattering. They have focused the problem of large tracking error, for which more torque is needed, and may even result in actuator saturation. It regulates torque of robust controller by defining new trajectories based on initial trajectory using Fuzzy logic, affecting the input torque and reducing the arriving time to target point. The output of control contains high frequency chattering. A five point averaging filter has been used to eliminate it. Kuo et al. [15] have used PID sliding mode controller in which single input radial basis function NN is used to tune switching gain, thus eliminates chattering phenomenon on reachable condition of sliding mode. Ahmed et al. [16] have proposed a PI sliding mode controller with matched uncertainties to ensure that the tracking error decreases asymptotically to zero. Y. Guo et al. [17] proposed adaptive Fuzzy sliding mode control, in which the membership function of control gain is updated online using adaptive Single Input Single Output (SISO) fuzzy system. This requires less information of robotic manipulator, thus simplifying the implementation of controller. Shyu et al. [18] have presented inverse dynamics with adaptive sliding mode control for a robot with bounded unknown uncertainties and disturbances. It does not require estimation of time varying inertia matrix. Small disturbances can also be tolerated.

V. PASSIVITY BASED CONTROL

The controllers based on this strategy depend on the passive nature of the rigid robot. Passivity based controllers have better robustness properties featuring robust stability with parameter variation.

For a passive system, that maps control input τ to a new variable r, i.e. the filtered version of error. A controller which closes the loop between $-r$ and τ will guarantee the asymptotic stability of both e and $\dot{e}$ [6].

Defining an auxiliary filtered tracking error variable $r(s)$ as

$$r(s) = H^{-1}(s)e(s) \tag{28}$$

Where

$$H^{-1}(s) = [sI_n + \frac{1}{s} K(s)] \tag{29}$$

K(s) is nxn matrix chosen such that *H(s)* is strictly proper and stable transfer function with relative degree of 1. Considering the following controller,

$$\tau = M(q)\{\ddot{q}_d + K(s)e\} + C(q,\dot{q})\left\{\dot{q}_d + \frac{1}{s} K(s)e\right\} + g(q) + K_v r \tag{30}$$

Substituting it in the robot dynamic equation yields

$$M(q)\dot{r} + C(q,\dot{q})r + K_v r = 0 \qquad (31)$$

It can be shown that both e and $\dot{e}$ are asymptotically stable. Fig. 3 shows the block diagram of passivity based control strategy.

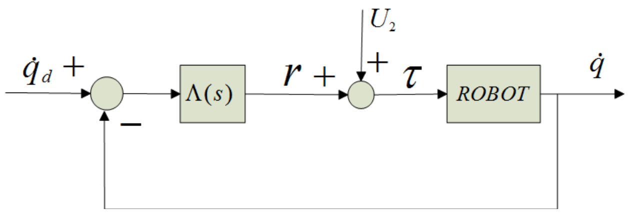

Figure 3. Passivity based control

The input torque to the robot is given by

$$\tau = \Lambda(s)\dot{e} + U_2 \qquad (32)$$

Where $\Lambda(s)$ is strictly proper and stable transfer function. The external input (τ) is bounded. From Fig. 3 we can write

$$r = \Lambda(s)\dot{e} \qquad (33)$$

Passivity theorem can be applied if $\Lambda(s)$ and U_2 are chosen appropriately and the resultant will be such that $\dot{e}$ and r are bounded in L_2 norm. As $\Lambda^{-1}(s)$ is proper and stable, so $\dot{e}$ is asymptotically stable.

Tang et al. [19] have combined adaptation with passivity based approach and proved the exponential stability without Persistent Excitation (PE). Due to past information and the averaging effect, it also gives a smoother behavior of the tracking error and parameter convergence under a weaker excitation condition. Arimoto [20] has used passivity of robot to derive robust and effective controllers from a modified form of robot dynamic (Euler-Lagrange) equation. Additionally he has shown that H-infinity controller can be designed to suppress disturbances without solving Hamilton Jacobian equation. The proposed controller is based on feedback PD controller with a regressor to estimate the dynamic parameters and a saturation position error to accelerate the convergence speed of set point and trajectory tracking control. He has demonstrated the controller performance of the dual finger robot with soft end of the deformable material. The motion equation of this robot is same as equation of pendulum with an indirect control term showing forces arising from contact areas between an object and the finger tips. Llama et al. [21] have presented an alternate global asymptotic stability proof for technique in [8]. It showed the mapping from a damping term to velocity error. The closed loop has a nonlinear feedforward passive term and a nonlinear feedback input passive block. The reported work of Shibata et al. [22] has combined two controllers, passivity based and Null Space (NS) force controller (the controller with no influence on end effector). The objective was to suppress force torque effects in manipulator dynamics, with a DOBC PD Work Space (WS) controller for end effector position control of a redundant robot manipulator. The NS has a stabilizing controller and a force controller. The stabilizing controller considers the stability of NS motion at the time of working, taking input torque as disturbance, for which L2 disturbance suppression property is used at each joint of the robot. A force PID controller is then used for the desired force response. The comparison is performed between the proposed scheme with a controller having position control in WS and a velocity feedback with DOBC in NS in two configurations, one at near singular configuration and other at a normal posture, which is not near the singular position. The proposed method has better performance near singular configuration.

For most of robot control systems, position and velocity measurement are required. The scheme proposed by Bouakrif et al. [23] requires only position measurement. The velocity measurements have been estimated via a special type of nonlinear disturbance observer, which uses passivity concepts. The observer forces the error dynamics to match a desired energy function. Semi global asymptotic stability for proposed system has been proved and estimate region of attraction has been specified.

VI. Disturbance Observer Based Controller

DOBC is a most effective and useful control scheme for robot manipulators. Coupling torques are considered as external disturbance in DOBC. Based on estimated disturbance torques, independent joint control can be made possible and hence a simple controller can be designed for a nominal model. DOBC can deduce external unknown disturbances without the use of additional sensors. DOBC can be used in independent joint control, friction estimation, position/force control and can provide signal for monitoring. DOBC has better performance with gain tuning method.

Let the dynamic equation for an n link nonlinear robotic manipulator is given by

$$M(q)\ddot{q} + C(q,\dot{q}) + g(q) + f(\dot{q}) = \tau \qquad (34)$$

Equivalent disturbance torque with inertia matrix is

$$\widehat{M}\,\ddot{q} + \tau_d(q,\dot{q},\ddot{q}) = \tau \qquad (35)$$

M is nxn diagonal matrix, τ_d is equivalent disturbance including all remaining terms, unmodeled dynamics such as nonlinearity, coupling effects and payload uncertainty. So a simple controller can be designed based on equivalent disturbance, which is estimated by disturbance observer shown in Fig. 4. [26] for i^{th} single axis and can be eliminated by adding the estimated disturbance signal to the control input. Let $P_{in}(s)$ be the nominal plant of real system, $P_i(s)$. $Q_i(s)$ be the low pass filter used to realize $P_{in}^{-1}(s)$. Input output relation can be written as

$$Y_i = G_{u_i y_i}(s)u_i + G_{\tau_{id} y_i}(s)\tau_{id} \qquad (36)$$

Where

$$G_{u_i y_i}(s) = \frac{P_i(s)P_{in}(s)}{P_{in}(s) + \left(P_i(s) - P_{in}(s)\right)Q_i(s)} \tag{37}$$

And

$$G_{\tau_{id} y_i}(s) = \frac{P_i(s)P_{in}(s)(1 - Q_i(s))}{P_{in}(s) + \left(P_i(s) - P_{in}(s)\right)Q_i(s)} \tag{38}$$

$Q_i(s)$ plays an important role in determining robustness and eliminating disturbances. If $Q_i(s) = 1$, (37) and (38) reduces to

$$G_{u_i y_i}(s) \approx P_{in}(s) \text{ And } G_{\tau_{id} y_i}(s) \approx 0$$

For disturbances having maximum frequency less than the cutoff frequency of $Q_i(s)$, the disturbance is rejected effectively and the plant acts as the nominal plant. Similarly if cutoff frequency of $Q_i(s)$ is chosen high, then the sensor noise will be rejected. A tradeoff between disturbance rejection and model mismatches versus sensor noise exists. If disturbance observer is employed for each joint of a manipulator, then the robot dynamics can be considered as Simple Equivalent Robot Dynamics (SERD) given by

$$\widehat{M}_n \ddot{q} = \tau \tag{39}$$

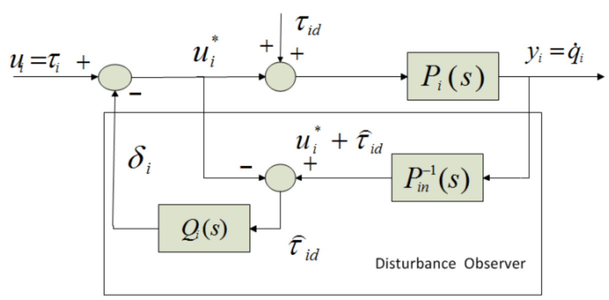

Figure 4. Block diagram of disturbance observer

Olsson et al. [24] have used DOBC for friction compensation in velocity loop of motion control system. As friction is dynamic, the control error due to nonlinearities such as friction can be examined and eliminated. Eom et al. [25] have proposed a method for force control of a robot without using force sensor by considering the contact of end-effecter with environment. The equivalent disturbances include modeling uncertainties and external force exerted by the environment. The exerted force can then be estimated from equivalent disturbance based on disturbance observer. In [26], a saturation element has been added with DOBC to compensate for cases when disturbance signal is greater than the toque limits of actuators. This method has been used for all joints with n-DOF manipulator to obtain a SERD model. In case of torque saturation, the desired acceleration of the nominal trajectory in Cartesian space is modified online using SERD. In the non-saturated regions, an integral action with respect to difference between nominal and modified trajectories is used to reduce path error. Yung et al. [27] have combined a decentralized sliding mode controller for compensating fast varying components of uncertainties with DOBC to compensate for low passed coupled uncertainties. Both strategies work in a coordinative way in each local subsystem to achieve excellent control performance.

In most cases, a perfect DOBC or perfect SMC may not be needed. Wang et al. [28] has presented a dynamic friction (LuGre) model-based friction compensator with PD controller for high speed linear motion system. Friction compensation error has been considered as a disturbance and a DOBC has been used to cancel it as well as external disturbances. The resulting DOBC friction compensator controller has good transient tracking performance and zero steady state error under external disturbances.

DOBC is used for each joint independently, and coupled linearly, by suppressing disturbances in specified frequency range with a low pass filter; the resulting system is in minimum phase configuration. But due to nonlinear and coupled structure of a robot and other nonlinear terms (friction and other uncertainties), it will not work better in all cases. Chen et al. [29] have presented a Nonlinear Disturbance Observer (NDO), in which VSC equivalent control method has been used for its formulation by knowing the upper and lower bounds of uncertainties. The disturbance estimated, is for minimum phase dynamical system with relative degree of one. Its performance at high frequency is only limited by measurement noise.

Chen et al. [30] have used NDO for estimating friction in a 2-link robot via feedforward term by using a revised friction model to reduce computations. The main controller used has been based on CTC without taking into account any disturbance. Global convergence has been proved by carefully selecting the observer gain. Yang et al. [31] have proposed a guaranteed robust controller with DOBC. A PI controller has been added in the inner loop with a novel robust nonlinear velocity controller with DOBC to compensate for velocity errors. The Input to State Stability (ISS) property of the overall nonlinear system is proved by using nonlinear damping terms. The effects of time constant on robustness are also discussed. Chen [32] has designed a controller for nonlinear system to achieve good tracking performance and stability. A nonlinear DOBC has been added to estimate the external disturbances and a feedback to compensate it. Global exponential stability has been proved by integrating both parts. Nikoobin et al. [33] have extended the work of [30] to n-link serial robot. A global condition for observer design parameter has been determined to guarantee the global asymptotic stability. In simulation the friction has been considered as external disturbance and modeling errors as internal disturbance. Mohammadi et al. [34] have introduced NDO for estimation of lumped disturbances, which include all internal and external disturbances. A feedforward term has been used to cancel the lump disturbance, due to which DOBC leads to fast tracking trajectory and smooth control action without the use of the large feedback terms. This method has no limitation of number of DOF, joint types and manipulator configuration. Tested for SCARA configuration, asymptotic trajectory tracking of the proposed scheme is guaranteed.

VII. CONCLUSION

A survey is presented on the most commonly used techniques for rigid robot control. Robotic manipulators have complex nonlinear dynamic structure with uncertain parameters. Any control technique to be chosen for controlling robot depends on required computational power, stability for the range of operation and other deciding factors. Each technique has some drawbacks, for example CTC gives a linear system with GAS but it requires exact knowledge of parameters, which is not possible in presence of disturbances and due to limited resolution of sensors. VSC is a good choice that guarantees stability and robustness in sliding mode, but in reaching phase, it is not invariant to disturbances. Also it has a 'sgn' function discontinuity, which may result in chattering phenomenon. Intelligent method may be used to reduce chattering. PBC offers simplicity in implementation, but can't give easily quantifiable measures. DOBC is a useful control strategy in which each joint dynamic is considered separately to make a simple equivalent robot dynamics. A NDO can be applied to compensate for nonlinear structure of robot. Table I summarizes the comparative analysis of various control schemes discussed.

VIII. ACKNOWLEDGEMENT

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TABLE I. COMPARISON OF CONTROL STRATEGIES

Controller	Advantages/Application	Drawbacks	Possible Solutions
Feedback linearization/Computed Torque Control (CTC).	• Nonlinearities of robot dynamics cancel out. • Guarantee Global Asymptotic Stability.	• Exact dynamic model and parameters are needed. • Gain of controller can't be kept constant. • Actuator saturation and friction are nonlinear terms to compensate among others. An intelligent controller like Fuzzy or NN must be used with CTC.	• Add a compensation term for compensating modeling uncertainties. • Determine nonlinear gain using Fuzzy approach to avoid torque saturation and errors due to friction or compensating torque for disturbances. • Use LGP for low computation and high learning accuracy to avoid torque saturation. • Add another nonlinear term to compensate for saturation nonlinearity as well as utilize full actuator capability, also to ensure fast response with less overshoot. • Use a robot dynamic model in conjunction with robot to eliminate disturbances and modeling uncertainties.
Variable Structure Compensator (VSC).	• Can be used for many nonlinear processes. • Give invariance to modeling uncertainties and disturbances in sliding mode.	• Reaching phase has no such invariance and robustness. • A sgn function may excite unmodeled dynamics and lead to Chattering phenomenon.	• Combination of FB linearization with VSC to eliminate uncertainties. A boundary layer compensator is used to avoid sharp transition, and hence chattering. • Use averaging filter to eliminate chattering. • Use single input radial basis function NN for turning switching gains, eliminate chattering and achieve global sliding controller. • PI SMC with matched uncertainties. • Use adaptive fuzzy SMC, in which membership function of control gain is updated online using SISO fuzzy system. • Adaptive SMC with inverse dynamics to tolerate for small unknown bounded uncertainties.
Passivity Based Controller (PBC).	• A body with passive nature will guarantee asymptotic stability.	• Error mapping to prove passivity. • Control gains can't be tuned in a straightforward way.	• Use adaptive scheme with passivity to confirm stability with PE. • Use nonlinear feedforward passive and nonlinear feedback block to show mapping for passivity and hence stability. • Passivity based nonlinear observer to estimate velocity and ensure semi global stability. • Combine another controller like DOBC for easy tuning.
Disturbance Observer Based Controller (DOBC).	• A simple nominal controller can be designed based on independent joint control. • DOBC can be used for friction estimation and position/force control. • It can provide signal for monitoring. • Gain tuning has a simple method.	• Complex friction compensation. • Torque saturation due to large disturbances. • The filter may be tuned either for low frequencies or high frequencies. • Nonlinear robot dynamics and nonlinear coupling of joints. • Rigorous stability can't be demonstrated.	• Use dynamic friction models like LuGre base compensators and a DOBC to estimate friction. • Add a saturation element to avoid actuator saturation, and modify trajectory. • Use decentralized sliding mode controller for high frequency disturbance compensation and DOBC for low frequency disturbances. • NDO is used to take into account nonlinear structure and nonlinear coupling. • Use a controller having guaranteed stability like PID or computed torque controller with DOBC to provide overall stability measure.

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