with the same gate width ($2 \times 30\mu m$) has a maximum stable gain of 11.6dB at 94GHz, as shown in Fig. 4*a*. We have also fabricated a four-stage distributed amplifier based on 0.15μm cascode passivated HEMTs with 11dB average gain and 89GHz bandwidth, as shown in Fig. 4*b*.

*Summary:* In conclusion, we have developed a 0.15μm InP-based HEMT MMIC technology, including silicon nitride passivation and selective gate recessing. By using this technology, a single stage amplifier with 10.2dB gain at 88GHz, and a distributed amplifier with a 11dB gain and 89GHz bandwidth, were demonstrated. This high gain is mainly related to the extremely low gate-drain feedback capacitance of our passivated HEMTs, for which the physical origins have been demonstrated.

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## Trajectory planning and robust adaptive control for underactuated manipulators

Jin-Ho Shin and Ju-Jang Lee

A stable, robust adaptive control method is proposed for underactuated manipulators in Cartesian space. It is considered that the passive joints have both no actuators and no brakes and thus swing freely.

*Introduction:* The dynamics and control problems of nonholonomic underactuated manipulators have attracted much attention in recent years [1 – 3]. Most of the control results for underactuated manipulators in previous work required an accurate dynamic model without considering any uncertainty and did not consider any singularity analysis. In this Letter, a globally stable, robust adaptive Cartesian control method is proposed for robot manipulators with free-swinging passive joints. Singularity-free Cartesian path planning is achieved to guarantee the availability of the control method.

*System description:* The dynamic equation of an *n*-link underactuated manipulator can be described as

$$M(q)\ddot{q} + F(q,\dot{q}) = u + d(t) = \begin{pmatrix} \tau_a + d_a(t) \\ O_p + d_p(t) \end{pmatrix} \quad (1)$$

where $q = (q_a^T \; q_p^T)^T \in \Re^n$ represents the joint positions, $q_a \in \Re^r$ is the vector of active joints, $q^p \in \Re^p$ is the vector of passive joints,

$$M(q) = \begin{pmatrix} M_{aa} & M_{ap} \\ M_{pa} & M_{pp} \end{pmatrix} = M^T(q) > 0$$

is the inertial matrix, $F(q, \dot{q}) = (F_a^T \; F_p^T)^T = C(q, \dot{q})\dot{q} + G(q)$ gives the Coriolis, centrifugal and gravitational torques, $\tau_a \in \Re^r$ is the actual torque vector, $O_p \in \Re^p$ is the zero vector, and $d(t) = (d_a^T \; d_p^T)^T \in \Re^n$ is an external disturbance vector bounded as $\|d(t)\| \leq d_{max}$.

The Jacobian relationship is $\dot{p}_e = J(q)\dot{q}$ where $p_e \in \Re^m$ is the manipulator's end-effector position and orientation vector. The Jacobian matrix $J(q)$ can be partitioned as $J(q) = (J_a(q) \; J_p(q)) \in \Re^{m \times n}$ where $J_a(q) \in \Re^{m \times r}$ and $J_p(q) \in \Re^{m \times p}$.

The dynamic equation in Cartesian space is now obtained as

$$\ddot{p}_e - b(q,\dot{q}) = D_a(q)\tau_a + D(q)d(t) \quad \in \Re^m \quad (2)$$

where $D_a(q)$, called the decoupling matrix for the system, is defined by $D_a(q) = \bar{J}_a(q)\bar{M}_{aa}^{-1}(q) \in \Re^{m \times r}$; also, $\bar{M}_{aa} = M_{aa} - M_{ap}M_{pp}^{-1}M_{pa} \in \Re^{r \times r}$, $\bar{J}_a = J_a - J_pM_{pp}^{-1}M_{pa} \in \Re^{m \times r}$, $D(q) = J(q)M^{-1}(q) \in \Re^{m \times n}$ and $b(q, \dot{q}) = \dot{J}(q, \dot{q})\dot{q} - J(q)M^{-1}(q)F(q, \dot{q})$.

The dynamic terms shown in eqn. 2 can be norm-bounded as follows: $\|D_a(q)\| \leq \theta_{d_a}$, $\|b(q,\dot{q})\| \leq \theta_{b_0} + \theta_{b_1}\|\dot{q}\|^2$, $\|D(q)\| \leq \theta_d$.

*Control system design:* The Cartesian tracking error ($e$) and the augmented error ($s$) are denoted by $e = p_e - p_{e_d}$ and $s = \dot{e} + \Lambda e$ where $p_{e_d} \in \Re^m$ is a desired trajectory of the end-effector and $\Lambda = \mathrm{diag}(\lambda_1, \lambda_2, ..., \lambda_m)$ with $\lambda_i > 0$.

We propose a robust adaptive Cartesian controller as follows:

$$\tau_a = \hat{D}_a^{\#}(q)(v_r - \hat{b}(q,\dot{q})) \in \Re^r, \; v_r = v + \Delta v \in \Re^m \quad (3)$$

$$v = \ddot{p}_{e_d} - (K + \Lambda)\dot{e} - K\Lambda e, \quad K = K^T > 0 \quad (4)$$

$$\Delta v = -\hat{\rho}\frac{\alpha}{h_\alpha(\|\alpha\|)}, \; \alpha = Rs \in \Re^m, \; R = R^T > 0 \quad (5)$$

$$\hat{\rho} = \hat{\theta}^T\psi, \; \hat{\theta}(0) \geq 0, \; \psi = (1 \quad \|\dot{q}\|^2 \quad \|\ddot{p}_{e_d}\| \quad \|\dot{e}\| \quad \|e\|)^T \quad (6)$$

$$\dot{\hat{\theta}} = \Gamma\left(\frac{\psi\|\alpha\|^2}{h_\alpha(\|\alpha\|)} - \sigma\hat{\theta}\right) \in \Re^5, \quad \Gamma = \Gamma^T > 0, \; \sigma > 0 \quad (7)$$

where $\hat{D}_a^{\#}(q) \in \Re^{r \times m}$ is a pseudoinverse matrix of $\hat{D}_a$ with the nominal dynamic parameters obtained as $\hat{D}_a^{\#} = \hat{D}_a^T(\hat{D}_a\hat{D}_a^T)^{-1}$ under the assumption of $r \geq m$, and the full-rankness of $\hat{D}_a$. $h_\alpha(\|\alpha\|)$ is a chattering alleviation function, for example $h_\alpha(\|\alpha\|) = \|\alpha\| + \epsilon$ with $\epsilon > 0$.

The closed-loop error dynamics for $s$ become $\dot{s} = -Ks + \Lambda v + \eta$ where $\eta = (D_a\hat{D}_a^{\#} - I_m)\,v_r + (b - D_a\hat{D}_a^{\#}\hat{b}) + D\,d(t)$ is the *lumped uncertainty* term and $I_m$ is an $m \times m$ identity matrix.

*Assumption 1:* $\|D_a\hat{D}_a^{\#} - I_m\| \leq \kappa_0 < 1$, $\|b - D_a\hat{D}_a^{\#}\hat{b}\| \leq \kappa_1 + \kappa_2\|\dot{q}\|^2$, $\|v_r\| \leq \|\ddot{p}_{e_d}\| + \kappa_3\|\dot{e}\| + \kappa_4\|e\| + \hat{p}$.

Thus, $\|\eta\| \leq \bar{\theta}_1 + \bar{\theta}_2\|\dot{q}\|^2 + \bar{\theta}_3(\|\ddot{p}_{e_d}\| + \hat{\rho}) + \bar{\theta}4\|\dot{e}\| + \bar{\theta}_5\|e\|$ where $\bar{\theta}_1 = \theta_{d_a}d_{max} + \kappa_1$, $\bar{\theta}_2 = \kappa_2$, $\bar{\theta}_3 = \kappa_0$, $\bar{\theta}_4 = \kappa_0\kappa_3$ and $\bar{\theta}_s = \kappa_0\kappa_4$.

*Theorem 1:* Under assumption 1, the proposed Cartesian control system (eqns. 3 – 7) guarantees that the tracking errors are globally uniformly ultimately bounded (GUUB).

*Proof:* Consider a Lyapunov function candidate

$$V = (1/2)\left\{s^TRs + (1 - \bar{\theta}_3)\tilde{\theta}^T\Gamma^{-1}\tilde{\theta}\right\} = (1/2)z^TPz \quad (8)$$

where $\tilde{\theta} = \hat{\theta} - \theta \in \Re^5$, $\theta_i = \bar{\theta}_i/(1-\bar{\theta}_3)$, and $z = (s^T \; \tilde{\theta}^T)^T$.

After manipulation we obtain

$$\dot{V} \leq -(1/2)z^TQz + w(\rho, \hat{\rho}, \|\alpha\|) \quad (9)$$

where $Q = \mathrm{diag}(2RK, (1-\bar{\theta}_3)\sigma)$ and $w(\rho, \hat{\rho}, \|\alpha\|) = (1/2)(1-\bar{\theta}_3)\theta^T\sigma\theta + \|\alpha\|[h_\alpha(\|\alpha\|) - \|\alpha\|]\,[\hat{\rho}\,\bar{\theta}_3 + \rho(1-\bar{\theta}_3)]/h_\alpha(\|\alpha\|)$.

Consequently, since both $s(t)$ and $\tilde{\theta}(t)$ are GUUB as $\|s(t)\| \leq [2V/\lambda_{min}(R)]^{1/2}$ and $\|\tilde{\theta}(t)\| \leq [2V/((1-\bar{\theta}_3)\lambda_{min}(\Gamma^{-1}))]^{1/2}$, the stable dynamics $s = \dot{e} + \Lambda e$ guarantees that the tracking errors $e$ and $\dot{e}$ are also GUUB. See [3] for details. ■

Here, if $\epsilon = 0$ and $\sigma = 0$ in the controller, the closed-loop control system is globally asymptotically stable.

*Singularity-free Cartesian path planning:* We now present a singularity-free path planning procedure as follows:

(i) *Step 1:* Obtain the dynamic singularity regions such that $|\mathrm{Det}(\hat{D}_a(q)\hat{D}_a^T(q))| \leq \epsilon_d$ for almost all joint configurations of the given manipulator where 'Det' represents the determinant of a matrix and $\epsilon_d$ is a very small positive constant.

(ii) *Step 2:* Obtain the semi-singular regions in Cartesian space corresponding to the singular regions in joint space via the kinematics. The *semi-singular* regions in Cartesian space may be or

may not be singular in joint space. Also, find the singularity-free regions in Cartesian space corresponding to only the nonsingular regions in joint space.

(iii) *Step 3:* Make a desired path or trajectory within the nonsingular regions in Cartesian space.

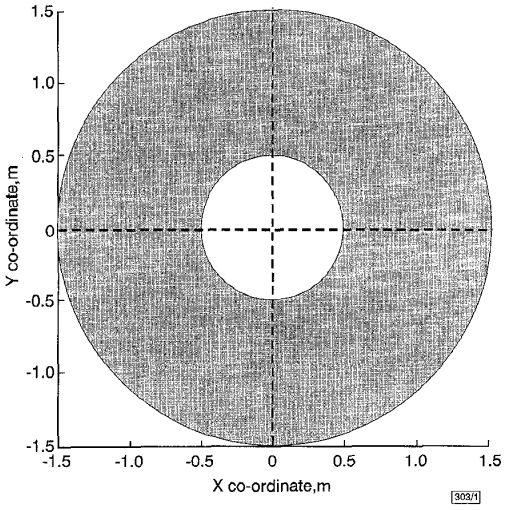


**Fig. 1** *Singularity-free regions in Cartesian space*

Boundary lines do not belong to nonsingular regions
◎ semi-singular region
○ nonsingular region

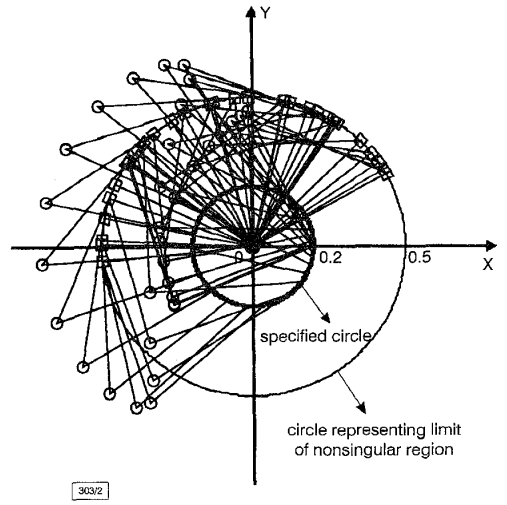


**Fig. 2** *Snapshot of robot motion for circle tracking task*

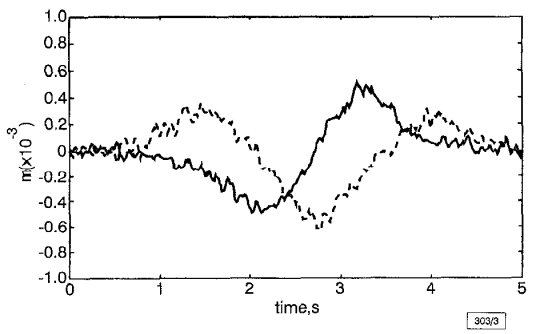


**Fig. 3** *Position tracking error (e)*

——— X-co-ordinate
– – – – Y-co-ordinate

*Simulation:* The simulated manipulator is a three-link planar robot arm with one passive joint moving on a horizontal plane [3]. It is assumed that the third joint ($q_3$) is passive. The numerical real and nominal robot parameters used are the same as those given in [3]. The disturbance is a bounded random noise.

The singular regions in joint space found for the simulated manipulator are as follows: $\Omega_1 = \{q : q_2 = 0(\text{rad}) \ \forall \ q_1,q_3\}$, $\Omega_2 = \{q : q_2 = \pi(\text{rad}) \ \forall \ q_1,q_3\}$, $\Omega_3 = \{q : q_2 = 2\pi(\text{rad}) \ \forall \ q_1,q_3\}$. Fig. 1 shows the singularity-free region in Cartesian space for the simulated underactuated robot. The robot task used is that the end-effector circulates once along the specified circle.

In the control simulation, the singularity-free desired path $x_{ed}^2(t) + y_{ed}^2(t) = 0.2^2$ is used. Simulation results for the circular motion of the end-effector are shown in Figs. 2 and 3.

*Conclusions:* A stable, robust adaptive Cartesian control with fault tolerance for underactuated manipulators has been proposed to overcome actuator and/or brake failures and uncertainties. The proposed control method does not need *a priori* knowledge of the accurate dynamic parameters and the exact uncertainty bounds. To guarantee the availability of the proposed controller, singularity-free Cartesian path planning has been achieved. The proposed control scheme is useful and robust for uncertain underactuated robot systems with many applications, such as fault-tolerant robots, robots working in hazardous environments (space, underwater, nuclear plants), etc.


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## Surface acoustic wave device design for gas sensing applications

M.I. Newton, T.K.H. Starke, G. McHale, M.R. Willis and A. Krier

A dual delay line surface acoustic wave device designed for gas sensing applications is described. The viability of this design is demonstrated using data showing the response to $NO_2$ with a sensitising layer of lead phthalocyanine.

*Introduction:* The use of surface acoustic wave (SAW) oscillators incorporating sensitising layers for gas detection has been extensively reported and reviewed [1, 2]. A dual delay line configuration using two identical SAW oscillators, one coated with a gas sensitive layer and one uncoated, is often employed to provide compensation for environmental changes such as temperature and pressure [3, 4]. Using a simple interdigital transducer on an appropriate piezoelectric substrate, surface acoustic (Rayleigh) waves are launched equally in both directions perpendicular to the fingers. This is normally considered to be undesirable in an oscillator circuit as the SAW energy launched in the opposite direction to the detection transducer provides an additional 6dB of attenuation to be overcome by the amplifier. In this work, an SAW design was investigated which used a separate interdigital transducer for the oscillator frequency detection utilising this 'unwanted' SAW component. This configuration removed the usual requirement for a