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Recall 
$$\dot{X} = J(\xi)\dot{\xi}$$
 for manipulator Jacobian  $J(\xi)$ 

If  $\dot{X} = V_{st}^{i}$ , then  $J_{st}^{i}(\xi) \in \mathbb{R}^{6m}$ 

If  $\dot{X} = V_{st}^{i}$ , then  $J_{st}^{i}(\xi) \in \mathbb{R}^{6m}$ 

Let  $n = 6$  so that we have a square  $J$ .

 $\dot{X} = J(\xi)\dot{\xi} \implies \ddot{X} = J(\xi)\dot{\xi} + J(\xi)\dot{\xi}$ 

Given  $\dot{y} = a_{\xi}$ , choose  $a_{\xi} := J^{-1}(a_{\chi} - J(\xi))$ 

(first outer-loop)

 $\dot{y} = J^{-1}(a_{\chi} - J(\xi)) \implies J(\xi) + J(\xi) = a_{\chi}$ 
 $\ddot{x} = a_{\chi} \leftarrow \text{new input}$ 
 $\ddot{x} = \ddot{x}\dot{x} - K_{\xi}(\ddot{x} - \ddot{x}\dot{x}) - K_{\chi}(\ddot{x} - \ddot{x}\dot{x}\dot{x})$ 
 $\ddot{x} = \ddot{x}\dot{x} - K_{\xi}(\ddot{x} - \ddot{x}\dot{x}\dot{x}) - K_{\chi}(\ddot{x} - \ddot{x}\dot{x}\dot{x}\dot{x})$ 
 $\ddot{x} = \ddot{x}\dot{x} + K_{\chi}\ddot{x} + K_{\chi}\ddot{x} = 0$  (closed-loop task  $\dot{x} = \dot{x}\dot{x} + \dot{x}\dot{x} + \dot{x}\dot{x} = 0$ )

Choose  $K_{\xi}$ ,  $K_{\xi} > 0$  then  $(\ddot{x}, \ddot{x}) = \dot{x}\dot{x}$ 

exponentially stable  $\Rightarrow x \rightarrow x\dot{x}$ 

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Adaptive Inverse Dynamics Control:  Deals with parametric uncertainty  Recall "linearity in the parameters"  M(g) \( \beta + C(g, \beta) \beta + G(g) = \textbf{Y}(g, \beta, \beta) \)  We will vary parameters in \( \hat{A}, \hat{C}, \hat{C} \) aver time (all we want to find \( \hat{C} \) st. \( \textbf{Y}(g, \beta, \beta) \)  \[ \text{Parameter estimate} \]  M\(\beta + C\beta + G = \mu := \hat{M} \alpha, \frac{1}{2} \hat{C} \hat{G} + \hat{G} \)  \[ \text{Parameter estimate} \]  M\(\beta + C\beta + G = \mu := \hat{M} \alpha, \frac{1}{2} \hat{C} \hat{G} + \hat{G} \)  \[ \text{Pug in } \alpha_s + \text{M}'(\hat{M} \alpha_s + \hat{C} \hat{g} + \hat{G} \hat{G} \)  \[ \text{Pug in } \alpha_s = \frac{1}{3}(t) - K_A \hat{g} - K_B \hat{g} \)  \[ \text{Suplify} \( (ex. 9-11 in SHV) \)  \[ \text{Purameter} \)  \[ \text{Parameter} \)  \[ \text{Parameter} \)  \[ \text{Pure of } \text{Pure of } \text{Parameter} \)  \[ \text{Pure of } \text{Pure of } \text{Pure of } \)  \[ \text{Pure of } Pur		Do	al s	ر ا	th	Do	rav	nef	ric	un	cor	tain	۸ <b>+</b> ٠	,			
M(g) $\ddot{g}$ + C(g, $\dot{g}$ ) $\dot{g}$ + G(g) = $\Upsilon(g, \dot{g}, \ddot{g})$ $\Xi$ We will vary parameters in $\hat{M}$ , $\hat{C}$ , $\hat{G}$ over time (all we want to find $\hat{\Xi}$ st. $\Upsilon(g, \dot{g}, \ddot{g})$ $\Xi$ = $\Upsilon(g, \dot{g}, \ddot{g})$ M $\ddot{q}$ + C $\dot{g}$ + G = $u$ := $\hat{M}$ $a_s$ + $\hat{C}$ $\dot{g}$ + $\dot{G}$ $\Rightarrow \ddot{q}$ = $M^{-1}$ ( $\hat{M}$ $a_s$ + $\hat{C}$ $\dot{g}$ + $\dot{G}$ )  Plug in $a_s$ = $\ddot{q}^3$ (t) - $K_a$ $\ddot{g}$ - $K_p$ $\ddot{g}$ , where $\ddot{g}$ = $q$ - $g$ simplify (ex. 9-11 in SHV) $\Rightarrow$ closed-loop $\ddot{q}$ + $K_a$ $\ddot{g}$ + $K_p$ $\ddot{g}$ = $\hat{M}^{-1}$ $\Upsilon(g, \dot{g}; \dot{g})$ $\Xi$ where $\Xi$ = $\bar{\Xi}$ - $\Xi$ is parametric error					•	123						,,,,,	`				
M(q) $\ddot{q}$ + C(q, $\dot{q}$ ) $\dot{q}$ + G(q) = $\Upsilon(q, \dot{q}, \ddot{q})$ $\Xi$ We will vary parameters in $\hat{M}$ , $\hat{C}$ , $\hat{G}$ over time (all we want to find $\hat{\Xi}$ st. $\Upsilon(q, \dot{q}, \ddot{q})$ $\Xi$ = $\Upsilon(q, \dot{q}, \ddot{q})$ M $\ddot{q}$ + C $\ddot{q}$ + G = $u$ := $\hat{M}$ $a_{\dot{q}}$ + $\hat{C}$ $\dot{q}$ + $\hat{G}$ $\Rightarrow \ddot{q}$ = $M^{-1}$ ( $\hat{M}$ $a_{\dot{q}}$ + $\hat{C}$ $\dot{q}$ + $\hat{G}$ )  Plug in $a_{\dot{q}}$ = $\ddot{q}$ (t) - $K_{\dot{q}}$ $\ddot{q}$ - $K_{\dot{p}}$ $\ddot{q}$ , where $\ddot{q}$ = $q$ - $\chi$ Simplify (ex. 9-11 in SHV) $\Rightarrow$ closed-loop $\ddot{q}$ + $K_{\dot{q}}$ $\ddot{q}$ + $K_{\dot{p}}$ $\ddot{q}$ = $\hat{M}^{-1}$ $\Upsilon(q, \dot{q}, \dot{q})$ $\Xi$	Re	دماا	" 1	ineo	ritz	, in	11	ne	para	me-	fers	17	vess	eV .			
We will vary parameters in $\hat{A}$ , $\hat{C}$ , $\hat{G}$ over time (a)  We want to find $\hat{\Theta}$ st. $Y(q, \dot{q}, \ddot{q}) = Y(q, \dot{q}, \ddot{q})$ Mig + $C\dot{q}$ + $G$ = $u$ := $\hat{M}$ $a_s$ + $\hat{C}$ $\dot{q}$ + $\hat{G}$ $\Rightarrow \ddot{q} = M^{-1}(\hat{M}a_s + \hat{C}\dot{q} + \hat{G})$ recall $\hat{M} = \hat{M} + \hat{G}$ = $a_s$ + $M^{-1}(\hat{M}a_s + \hat{C}\dot{q} + \hat{G})$ recall $\hat{M} = \hat{M} + \hat{G}$ Plug in $a_s$ = $\ddot{q}^a(t)$ - $K_a \ddot{q}$ - $K_p \ddot{q}$ , where $\ddot{q}$ = $q$ - $Simplify$ (ex. 9-11 in SHV) $\Rightarrow$ closed -loop $\ddot{q}$ + $K_A \ddot{q}$ + $K_p \ddot{q}$ = $\hat{M}^{-1} Y(q, \dot{q}\dot{q}) \tilde{\Phi}$ where $\tilde{\Phi} = \hat{\Phi} - \bar{\Phi}$ is parametric error	1 1														pare	neter	
We want to find $\widehat{\mathfrak{S}}$ st. $Y(q, \dot{q}, \ddot{q}) \underbrace{\mathfrak{F}} = Y(q, \dot{q}, \ddot{q})$ M\vec{q} + C\vec{q} + G = \omega := \hat{M} a_s + \hat{C} \vec{q} + \hat{G})  \Rightarrow \vec{q} = \hat{M}^{-1} \left( \hat{M} a_s + \hat{C} \vec{q} + \hat{G} \right)  \Rightarrow \vec{q} = \hat{q} + \hat{M}^{-1} \left( \hat{M} a_s + \hat{C} \vec{q} + \hat{G} \right)  \Rightarrow \text{Plug} in  \alpha_s = \vec{q}^d(t) - \kappa_s \vec{q} - \kappa_s \rightarrow \kappa_s \vec{q} - \kappa_s \rightarrow \hat{q} + \kappa_s \vec{q} - \left( \hat{q} \vec{q} + \kappa_s \vec{q} \right)  \Rightarrow \text{Cosed} - \loop  \vec{q} + \kappa_s \vec{q} + \kappa_s \vec{q} = \hat{M}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}}  \Rightarrow \hat{k_s} \vec{\vec{q}} + \kappa_s \vec{q} = \vec{\mathfrak{M}}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}}  \Rightarrow \hat{k_s} \vec{\vec{q}} + \kappa_s \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{M}}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}}  \Rightarrow \hat{k_s} \vec{\vec{q}} + \kappa_s \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{M}}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}}  \Rightarrow \hat{k_s} \vec{\vec{q}} + \kappa_s \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{M}}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}}  \Rightarrow \hat{k_s} \vec{\vec{q}} + \kappa_s \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{G}}^{-1}  Y(q, \vec{q} \vec{q} \vec{q} \right) \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{G}}^{-1}  \vec{\mathfrak{G}}{\mathfrak{G}} \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{G}}^{-1}  \vec{\mathfrak{G}}{\mathfrak{G}} \vec{\mathfrak{G}}{\mathfrak{G}} = \vec{\mathfrak{G}}^{-1}  \vec{\mathfrak{G}}{\mathfrak{G}} \vec{\mathfrak{G}}{\mathfrak{G}} \vec{\mathfrak{G}}{\mathfrak{G}}} \vec{\mathfrak{G}}{\mathfrak{G}} \vec{\mathfrak{G}}{\ma		Mι	5) <b>g</b>	+ (	CL <sub>g</sub> ,	8) 8	+	GG	<b>)</b> =	Y	(q, q	;, ÿ)	0				
We want to find $\widehat{\mathfrak{G}}$ st. $Y(q, \dot{q}, \ddot{q}) \underline{\mathfrak{G}} = Y(q, \dot{q}, \ddot{q})$ M\vec{q} + C\vec{q} + G = \omega := \hat{M} a_s + \hat{C} \vec{q} + \hat{G})  \Rightarrow \vec{q} = \hat{M}^{-1} \left( \hat{M} a_s + \hat{C} \vec{q} + \hat{G} \right)  \Rightarrow \vec{q} = \vec{q}^{-1} \left( \hat{M} a_s + \hat{C} \vec{q} + \hat{G} \right)  \Rightarrow \text{recall} \hat{M} = \hat{M} + \text{C} \vec{q} + \hat{G} \right)  \Rightarrow \text{Rug} in  \alpha_s = \vec{q}^{\dagger}(t) - \kat{K}_s \vec{q} - \kat{K}_p \vec{q} - \kat{K}_p \vec{q} + \kat{K}_p \vec{q} = \hat{M}^{-1} \text{Y}(q, \vec{q} \vec{q}) \vec{\text{G}}  \Rightarrow \text{Cosed} - \text{loop}  \Rightarrow \text{cosed} - \text{Loop}  \Rightarrow \text{Loop} \vec{q} = \hat{M}^{-1} \text{Y}(q, \vec{q} \vec{q}) \vec{\text{G}}  \Rightarrow \text{Degree}  \Rightarrow \text{Loop} \vec{q} = \hat{M}^{-1} \text{Y}(q, \vec{q} \vec{q}) \vec{\text{G}}  \Rightarrow \text{Loop}  \Rightarrow \text{Loop} \vec{q} = \hat{M}^{-1} \text{Y}(q, \vec{q} \vec{q}) \vec{\text{G}}	We	, w	:11	vary	, b	ara	met	ters	iv	j	۹, á	Ĉ, ĉ	· - c	n es	tin	e (.	ada
(parameter estimate) $M_{3}^{2} + C_{3}^{2} + G = u := \hat{M} a_{3}^{2} + \hat{C}_{3}^{2} + \hat{G}$ $\Rightarrow \ddot{q} = M^{-1} \left( \hat{M} a_{3}^{2} + \tilde{C}_{3}^{2} + \tilde{G} \right)$ $= a_{3}^{2} + M^{-1} \left( \hat{M} a_{3}^{2} + \tilde{C}_{3}^{2} + \tilde{G} \right)$ Plug in $a_{4}^{2} = \ddot{q}^{4}(t) - K_{4} \ddot{q}^{2} - K_{5} \ddot{q}^{2}$ , where $\ddot{q} = q^{-1}$ $\Rightarrow \text{closed-loop}$ $\ddot{q} + K_{4} \ddot{q}^{2} + K_{5} \ddot{q}^{2} = \hat{M}^{-1} \Upsilon(q, \dot{q}, \dot{q}) \tilde{\Theta}$ where $\tilde{\Xi} = \hat{\Theta} - \Theta$ is parametric error	الما	142	a. 10 ±	ر حد	<u>۲</u> ,	, d	څ	7	c <i>t</i> :	7	7(,	٠١	Æ	_	V /		۱.
$M\ddot{q} + C\dot{q} + G = u := \hat{M} a_{s} + \hat{C} \dot{q} + \hat{G} \qquad (\#)$ $\Rightarrow \ddot{q} = M^{-1} \left( \hat{M} a_{s} + \tilde{C} \dot{q} + \tilde{G} \right) \qquad \text{recall } \hat{M} = \tilde{M} + \tilde{M} + \tilde{G} \dot{q} + \tilde{G} $ $= a_{s} + M^{-1} \left( \hat{M} a_{s} + \tilde{C} \dot{q} + \tilde{G} \right)$ $\text{Plug in } a_{s} = \ddot{q}^{s} (+) - K_{s} \dot{\tilde{q}} - K_{p} \dot{\tilde{q}} \qquad \text{where } \tilde{q} = q - \tilde{G} \text{ is parametric error}$ $\Rightarrow \text{closed-loop}$ $\ddot{q} + K_{s} \dot{\tilde{q}} + K_{p} \ddot{\tilde{q}} = \hat{M}^{-1} \Upsilon(q, \dot{q}, \dot{q}) \tilde{G}$ $\text{where } \tilde{G} = \hat{G} - \tilde{G} \text{ is parametric error}$				10						4	- (8,	8,8	2		<u> </u>	6, <b>4</b> , 9	5 ) <b>'</b>
$\Rightarrow \ddot{q} = M^{-1} \left( \hat{M} a_1 + \tilde{C} \dot{q} + \tilde{G} \right) \qquad \text{recall } \hat{M} = \hat{M} + \tilde{M} + $						(Par	esti	not	<b>e</b> )								
$\Rightarrow \ddot{q} = M^{-1} \left( \hat{M} a_1 + \tilde{C} \dot{q} + \tilde{G} \right) \qquad \text{recall } \hat{M} = \hat{M} + \tilde{M} + $								•									
$= a_{s} + M^{-1}(\widetilde{M}a_{s} + \widetilde{c}\dot{q} + \widetilde{G})$ Plug in $a_{s} = \ddot{q}^{d}(+) - K_{s}\dot{\tilde{q}} - K_{p}\tilde{q}$ , where $\tilde{q} = q^{-1}$ $\begin{cases} Simplify & (ex. 9-11 \text{ in SHV}) \end{cases}$ $\Rightarrow closed - loop$ $\ddot{q} + K_{s}\dot{\tilde{q}} + K_{p}\tilde{q} = \widetilde{M}^{-1}\underline{Y}(q,\dot{q})\widetilde{p}$ $\text{where } \widetilde{\Xi} = \widehat{\Xi} - \underline{\Xi} \text{ is parametric error}$	M	}	Сġ	+ G	, =	u:	=	Â,	ع <sub>ه</sub> ۱	· ĉ	ġ 1	- ĉ	•			(#)	
$= a_{g} + M^{-1}(\widetilde{M}a_{g} + \widetilde{c}_{g} + \widetilde{G})$ Plug in $a_{g} = \widetilde{q}(t) - K_{g}\widetilde{q} - K_{p}\widetilde{q}$ , where $\widetilde{q} = q^{-1}$ $\begin{cases} \text{Simplify (ex. 9-11 in SHV)} \end{cases}$ $\Rightarrow \text{closed-loop}$ $\widetilde{q} + K_{g}\widetilde{q} + K_{p}\widetilde{q} = \widetilde{M}^{-1} \underline{Y}(q, \widetilde{q}, \widetilde{p}) \widetilde{\Theta}$ where $\widetilde{\Xi} = \widehat{\Theta} - \overline{\Theta}$ is parametric error	=>			ا- ا	1 3		+	~	. +	~`	)					\ _ A	
Plug in $\alpha_{g} = \ddot{q}^{3}(t) - K_{A}\ddot{q} - K_{P}\tilde{q}$ , where $\ddot{q} = q^{-1}$								'					Y	reca	AI /	4 = <i>j</i> u	<b>\</b> + <i>/</i> -
Plug in $\alpha_g = \ddot{q}^d(t) - K_d \ddot{q} - K_p \ddot{q}$ , where $\ddot{q} = q - \frac{1}{2}$			= (	a,	- ^	۷-, (	Mo	٦ <sub>9</sub> +	č	) <b>-</b> ĉ	<del>)</del>						
Simplify (ex. 9-11 in SHV) $\Rightarrow \text{closed-loop}$ $\tilde{q} + K_{A} \tilde{q} + K_{P} \tilde{q} = \tilde{\mathcal{M}}^{-1} Y(q, \tilde{q}, \tilde{g}) \tilde{\Theta}$ where $\tilde{\Theta} = \hat{\Theta} - \bar{\Theta}$ is parametric error	PI											,	L	we	ve	~ ~ = 0	<b>?</b> -
$\Rightarrow closed - loop$ $\ddot{q} + K_{A} \dot{\ddot{q}} + K_{P} \ddot{q} = \hat{\mathcal{M}}^{-1} \underline{Y}(q, \dot{q}, \ddot{g}) \underline{\tilde{\Theta}}$ where $\underline{\tilde{\Theta}} = \hat{\overline{\Theta}} - \underline{\overline{\Theta}}$ is parametric error				5												y	)
$\ddot{q} + K_{\lambda} \dot{\dot{q}} + K_{\rho} \ddot{q} = \hat{\mathcal{M}}^{-1} \underline{Y}(q, \dot{q}, \dot{q}) \underline{\widetilde{\Theta}}$ where $\underline{\widetilde{\Theta}} = \hat{\underline{\Theta}} - \underline{\overline{\Theta}}$ is parametric error				}	Sim	plify	(e	x.	9-11	in s	SHV)						
$\ddot{q}$ + $K_{A}\ddot{q}$ + $K_{P}\ddot{q}$ = $\hat{\mathcal{A}}^{-1}$ $Y(q,\dot{q}\dot{g})$ $\tilde{\Theta}$ where $\tilde{\Xi}$ = $\hat{\Theta}$ - $\Theta$ is parametric error				V													
where $\widetilde{\Phi} = \widehat{\Phi} - \overline{\Phi}$ is parametric error	=	ck	sed	-10	°P												
where $\widetilde{\Xi} = \widehat{\Phi} - \overline{\Phi}$ is parametric error			; q +	K	i i	K	P 9	-	Â-'	<b>Y</b> (	3, ĝ 8	) <u>ছ</u>					
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					-											Ve	cfe

Let	$e = \begin{bmatrix} \hat{9} \\ \hat{9} \end{bmatrix}$ be tracting error state vector
	$\begin{bmatrix} O & I \\ -\kappa_{P} & -\kappa_{A} \end{bmatrix} \qquad B = \begin{bmatrix} O \\ I \end{bmatrix}$
	designal Huruitz by choice of Kp, K& >0  (all e-values are in LHS of complex plane, i.e. all e-values have negative real part)
⇒ė	= Ae + B A Y(q, q, q) &
	= Ae + B \$\vec{\P}{\P} \vec{\P}{\pi} \cdots \text{where} \overline{\P}:= \hat{\P}' \gamma(\beta; \vec{\pi}; \vec{\pi})
	To be continued!