Bimanual Haptic Telepresent Control and its Application to Deactivation of Mines:

Concepts, Implementation, and Evaluation

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Abstract

This presentation discusses a novel approach to support disposal of explosive ordnances by application of bimanual haptic telepresent control techniques. For improved task execution the proposed system enables a human operator to perceive multimodal feedback, in particular detailed kinesthetic and tactile feedback at arms and fingers, from a remote task environment. Details of the developed experimental setup, comprising stereo vision, an active two-handed human system interface and a corresponding two-arm teleoperator, are presented. Furthermore a novel structure adapting scheme for control of the force feedback display and the manipulator arms is introduced. Usability and effectiveness of the bimanual telepresent control system are demonstrated by focusing and evaluating as a most relevant task scenario, the execution of mine defusing operations in a remote task environment.

Related Publications

Schmidt, G.; Kron, A.:
Haptic Telepresent Control Technology Applied to Disposal of Explosive Ordnances: Principles and Experimental Results. Proc. of the IEEE Int. Symposium on Industrial Electronics, *ISIE'05* Dubrovnik, Croatia, pp. 1503-1510.

Kron, A.; Schmidt, G.:
Stability and Performance Analysis of Kinethetic Control Architectures for Bimanual Telepresence Systems.
J. of Intelligent and Robot Systems (2006) 46,
Springer Science +Business Media B.V., pp. 1 -26.

Baier, H.; Schmidt, G.:
Transparency and Stability of Bilateral Kinesthetic Teleoperation with Time- Delayed Communication.
J. of Intelligent and Robot Systems (2004) 40:, 1-22, p. 1-12.

Background: Disposal of Explosive Ordnances (EOD),

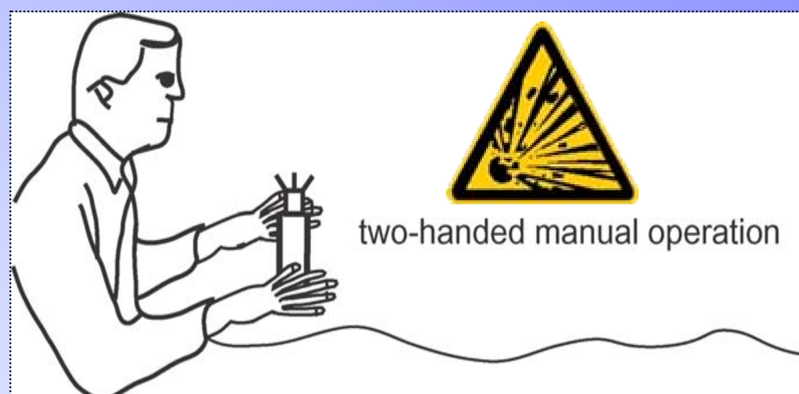
Removal of duds...

Demining...

Terroristic attacks...

... require human interventions in military and civil areas

- Operations are
  - + hazardous
  - + delicate
  - + complex
  - + expensive



- Experts act manually close to the explosive object

➔ Demand for assistance by remote control

Outline

- **State-of-the-art remote EOD**
- Telepresent control
- Bimanual haptic telepresence system
  - hardware setup
  - control architecture
  - safety features
- Experimental results from typical EOD scenario

State-of-the-art Technology for Remote EOD

system example: Revolution, REMOTEC, UK

- mobile platform
- single-arm manipulator
- direct visibility
- simple control panel
- radio communication

Major deficiencies:

- simple actions only
- visual feedback only
- non-intuitive operation
- confined feeling of presence

➔ Complex actions at the explosive still need manual intervention

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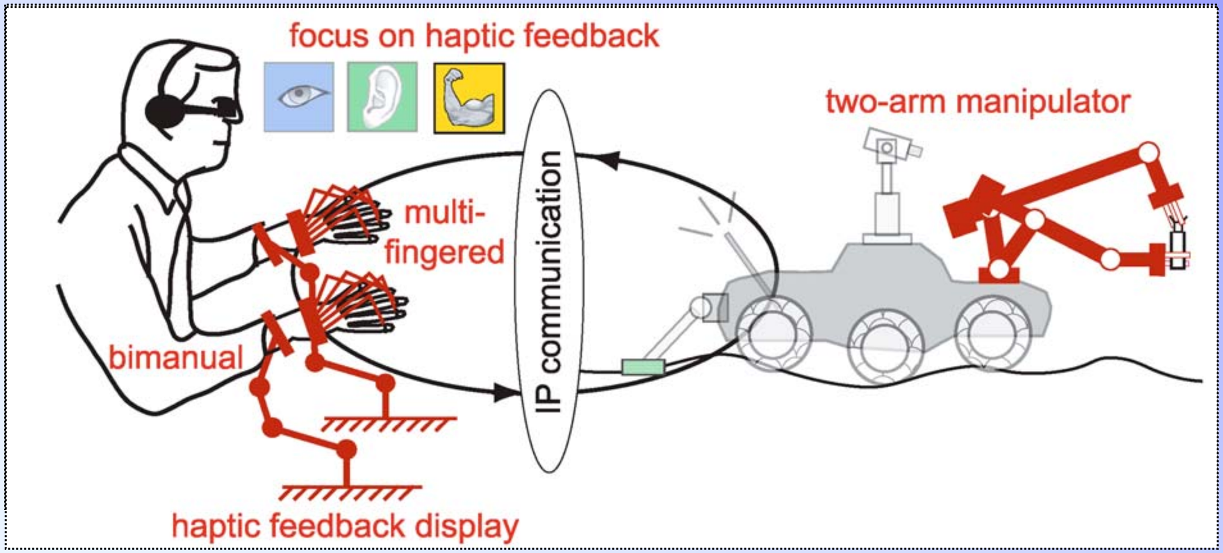
Advanced Remote EOD . . .

. . . should provide an increased sensation of operator immersiveness via

- multimodal perceptional feedback,
  e.g. haptics = touch and force, stereo vision
- two-arm manipulator system
- intuitive human system interface (HSI)

➔ Apply haptic telepresence control technology to EOD



Two-arm manipulator
and stereo vision
on mobile platform

What I hear I forget,
what I see I remember,
what I touch I understand.

Confucius 551 – 479 BC

Outline

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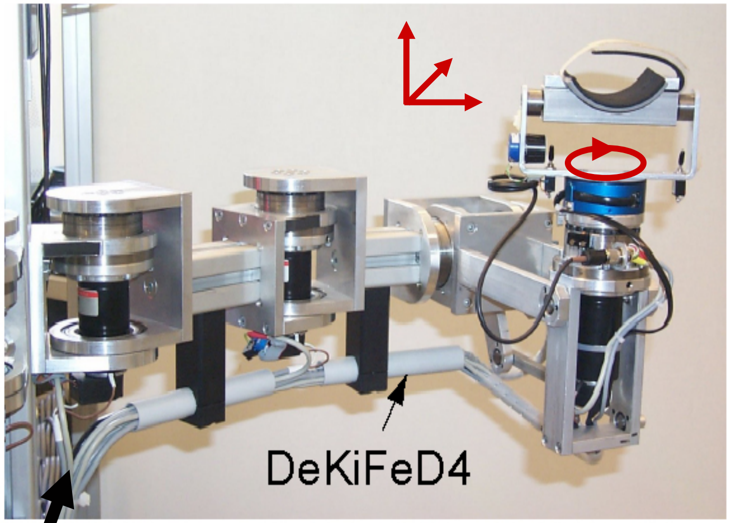
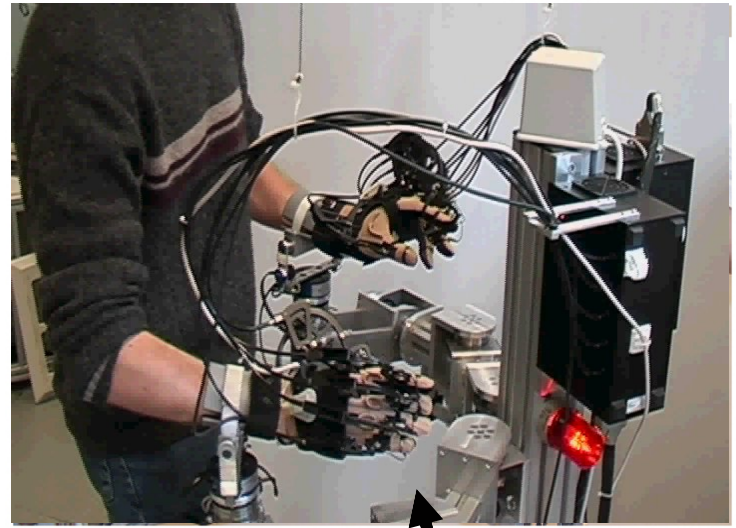
Haptic Feedback Display

Parallel wrist and finger force feedback display:

(ii) Finger kinesthetic display



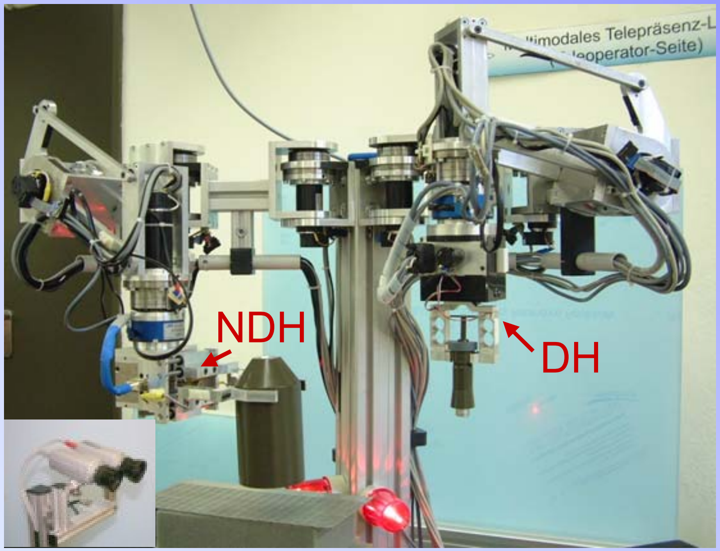


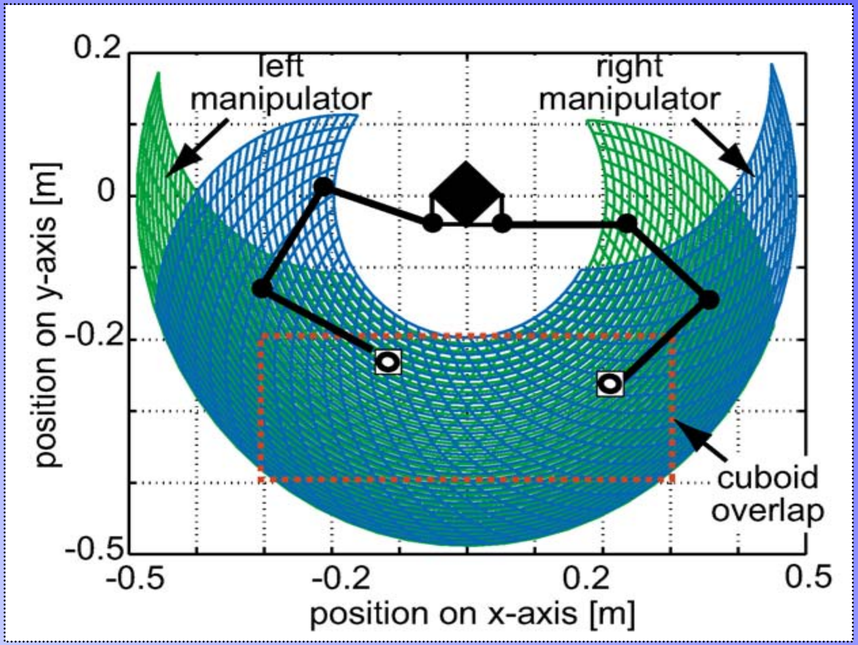
(i) Powerful desktop kinesthetic feedback device

(iii) Bimanual display with mirrored joint configuration

- SCARA type, 4 active Cartesian DoFs (3 translations, 1 rotation)
- DC motors with Harmonic Drives
- wrist forces/torques: 120 N, 20 Nm; finger forces: 10 N
- force/torque sensor

Two-arm Manipulator





Gripper configuration

- non-dominant hand (NDH): stable grasp, horizontally arranged jaws
- dominant hand (DH): precise action, vertically arranged jaws

Workspace

- large overlap (60x20x30 cm^3)

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Control Architecture for Wrist Kinesthetic Subsystem

requiring local control algorithms for master (display) and slave (manipulator)

Objectives:

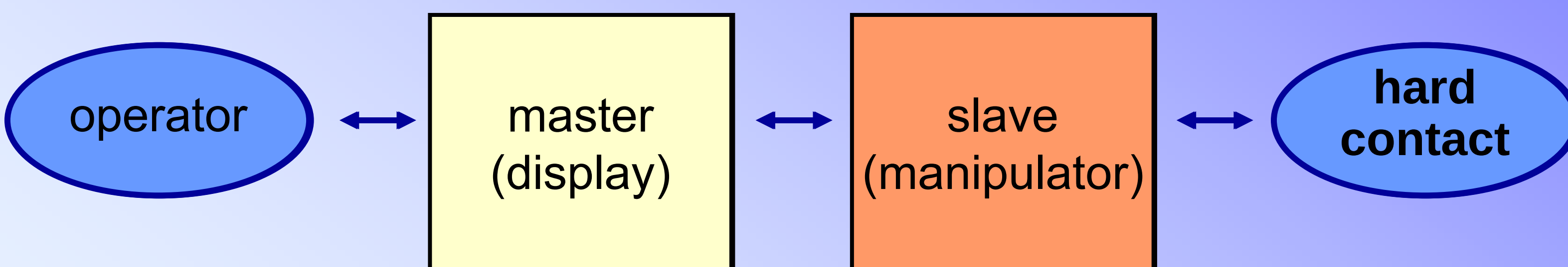
- robust stability
- realistic force feedback (= transparency)

Assumptions:

- communication delay < 5ms
- force, velocity data available

⌁ Fixed control law for free motion or hard contact **not** appropriate

New paradigm: concept of dual-hybrid teleoperation [Reboulet, 1995]



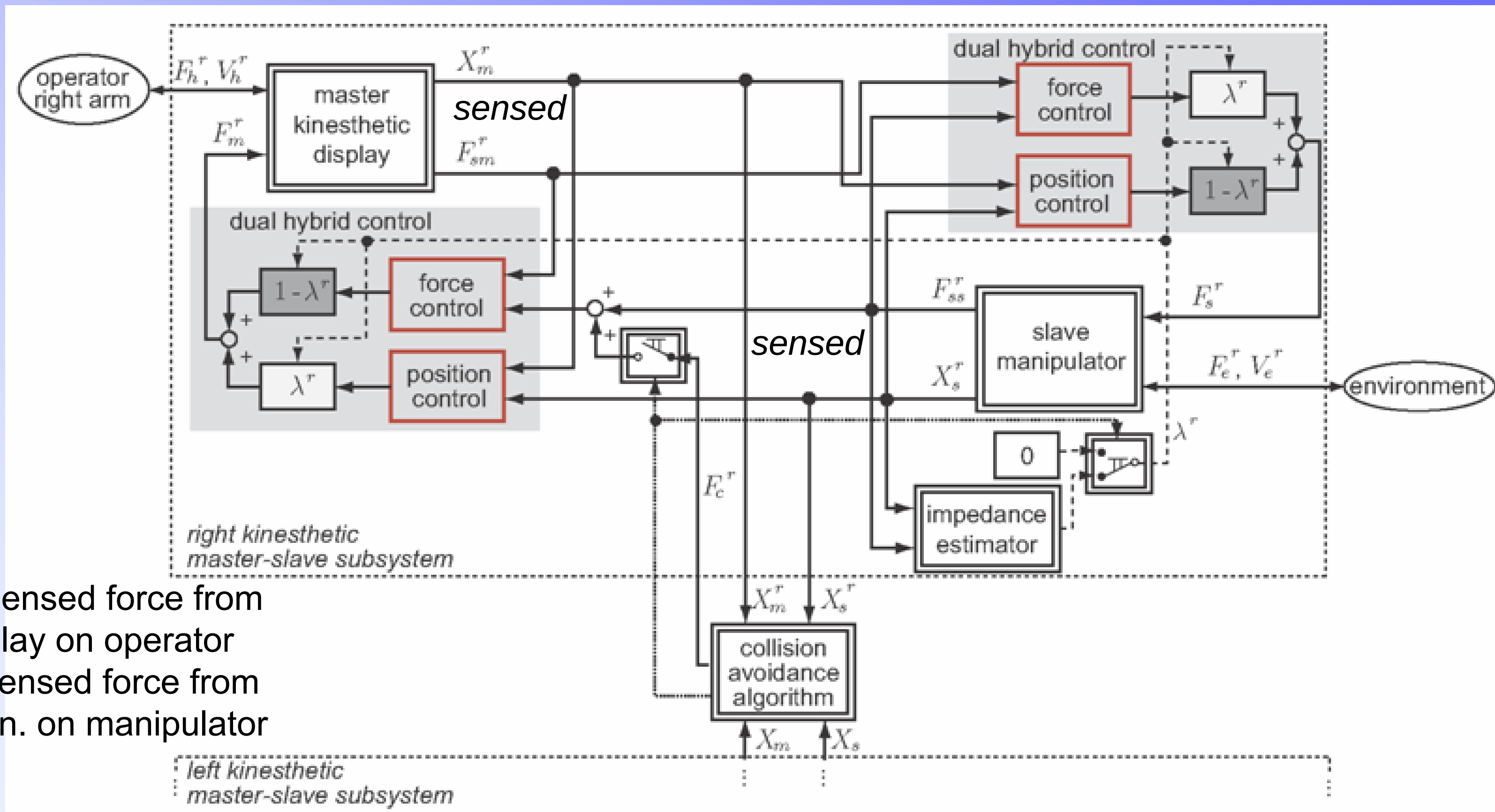
Operator intent:
input motion / input force

position source / force source
with
force sensor / position sensor

force source / position source
with
position sensor / force sensor

➔ Changing contact requires adaptation of control laws

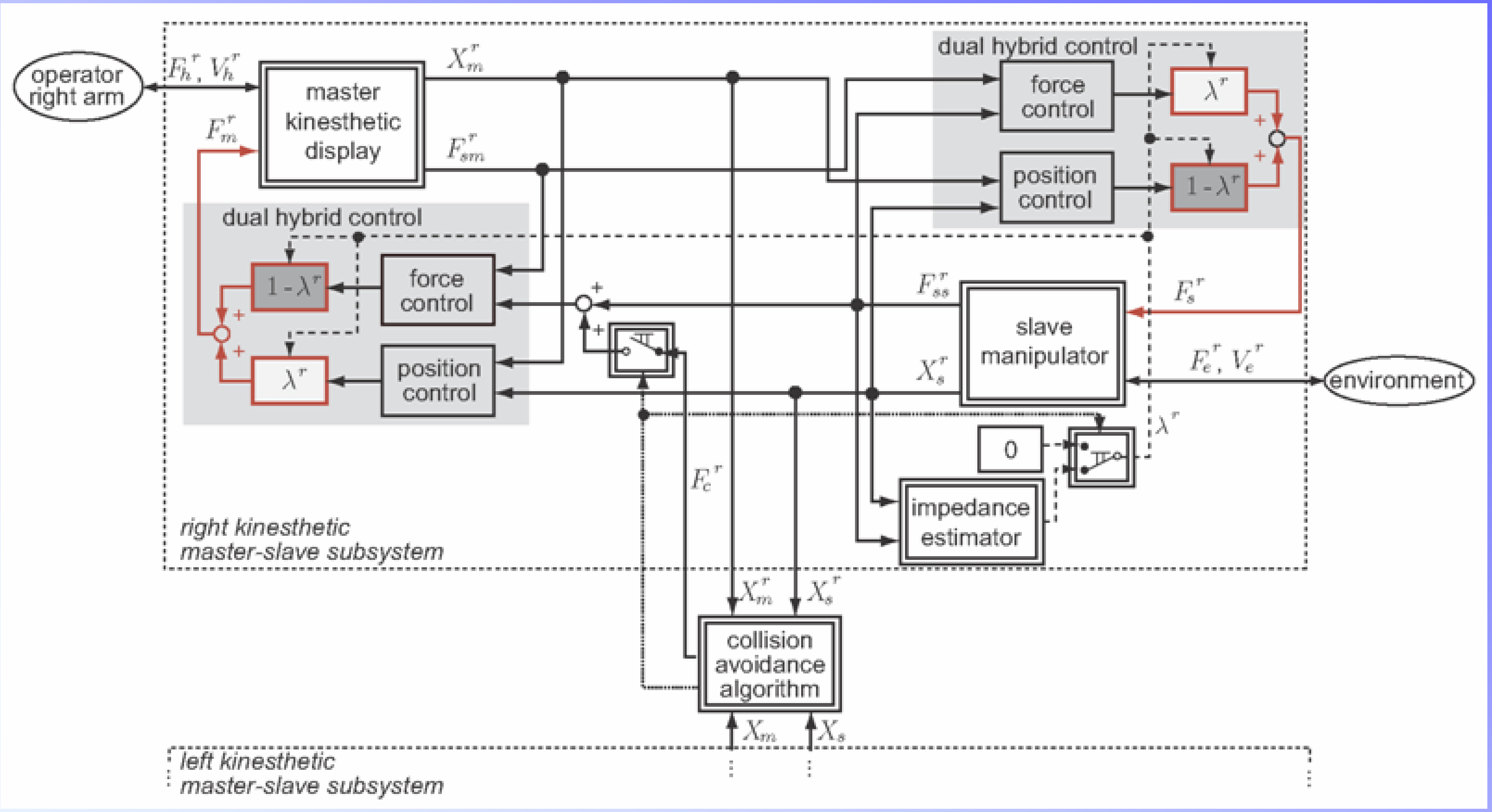
Bi-manual Kinesthetic Control Architecture



- **F_{sm}**: sensed force from display on operator
- **F_{ss}**: sensed force from environ. on manipulator

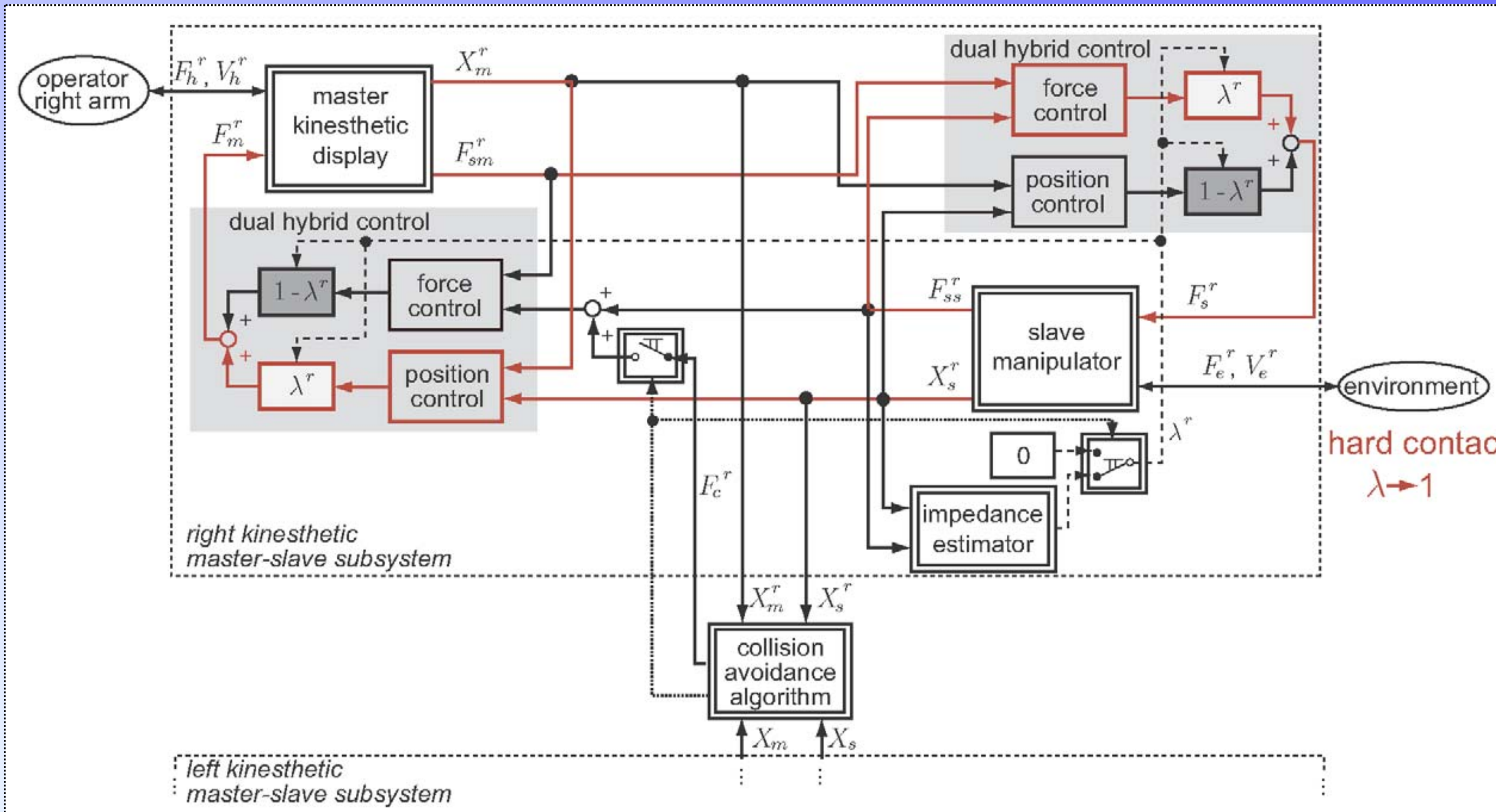
- sensor-based force controller
- state space position controller

Bi-manual Kinesthetic Control Architecture



- summation of controller outputs weighted by $0 < \lambda < 1$
- duality of weighting λ on master and slave site

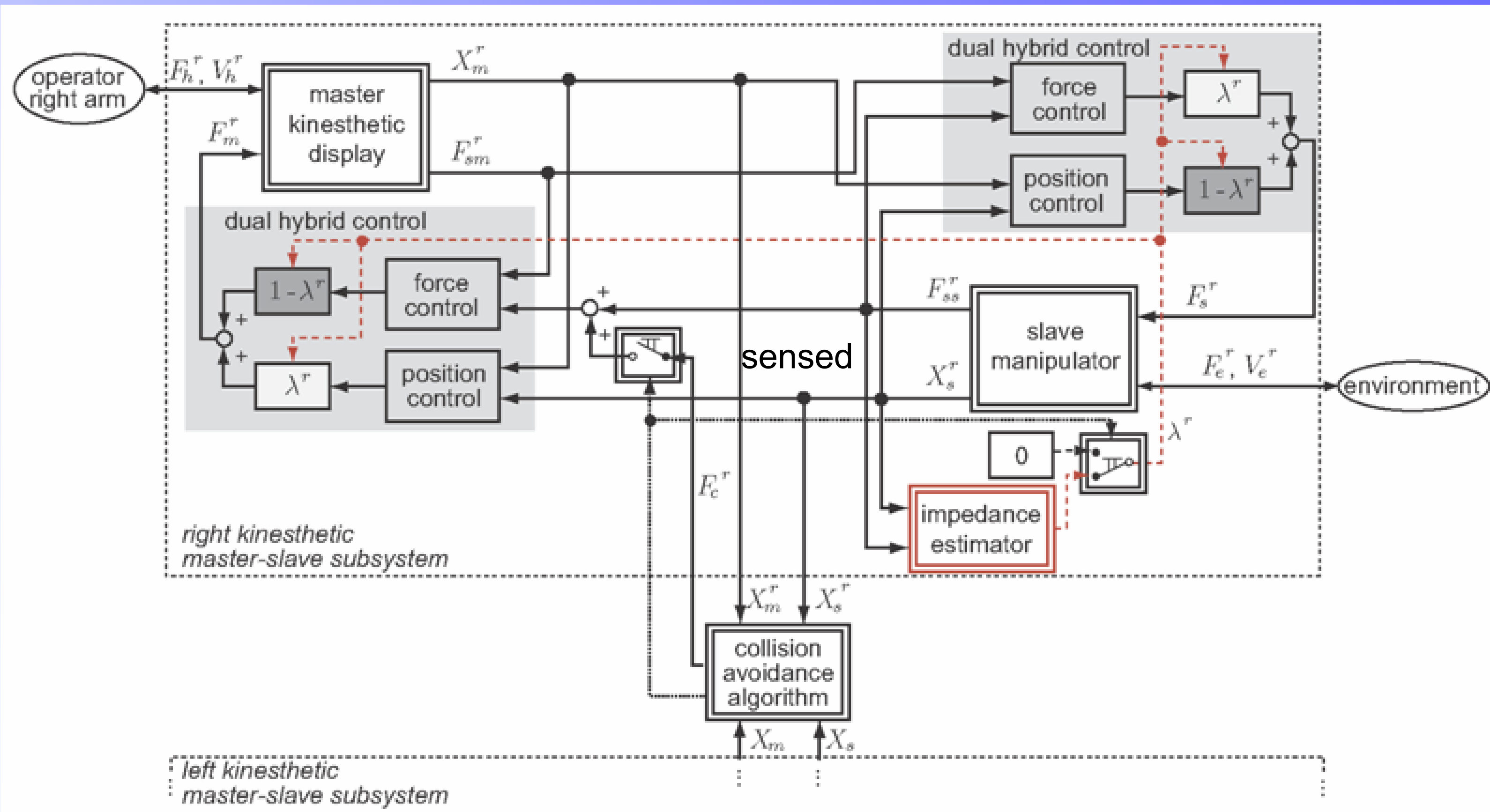
Adaptation of Control Laws



- free motion: $\lambda \approx 0$
- hard contact : $\lambda \approx 1$

➔ Adaptation assures stability <u>and</u> realistic environmental feedback (transparency)

Environmental Impedance Estimation



- on-line estimation using manipulator force/position data
- impedance model and recursive least square algorithm
- weighting factor λ → normalized impedance

Impedance Estimator

- Identification of 1st order impedance model

$$\hat{Z}_e = \hat{b}_e + \hat{k}_e / s$$

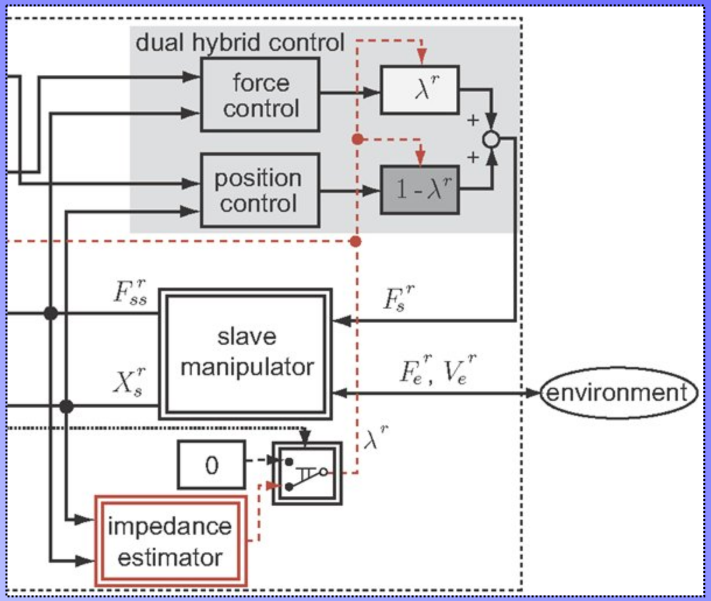
  by recursive least square algorithm
  Input: slave position and velocity
  Output: slave force

- *Virtual impedance* measure with fixed frequency $\omega_u = 20 \ \text{rad/s}$

$$\tilde{Z}_e = |\hat{Z}_e| \Big|_{\omega=\omega_u} = \sqrt{\hat{b}_e^2 + \frac{\hat{k}_e^2}{\omega_u^2}}$$

- Preceding tests for identification of $\tilde{Z}_{e,max}$
- Normalized weighting factor defined as

$$\lambda = \tilde{Z}_e / \tilde{Z}_{e,max} \ \in [0,1]$$



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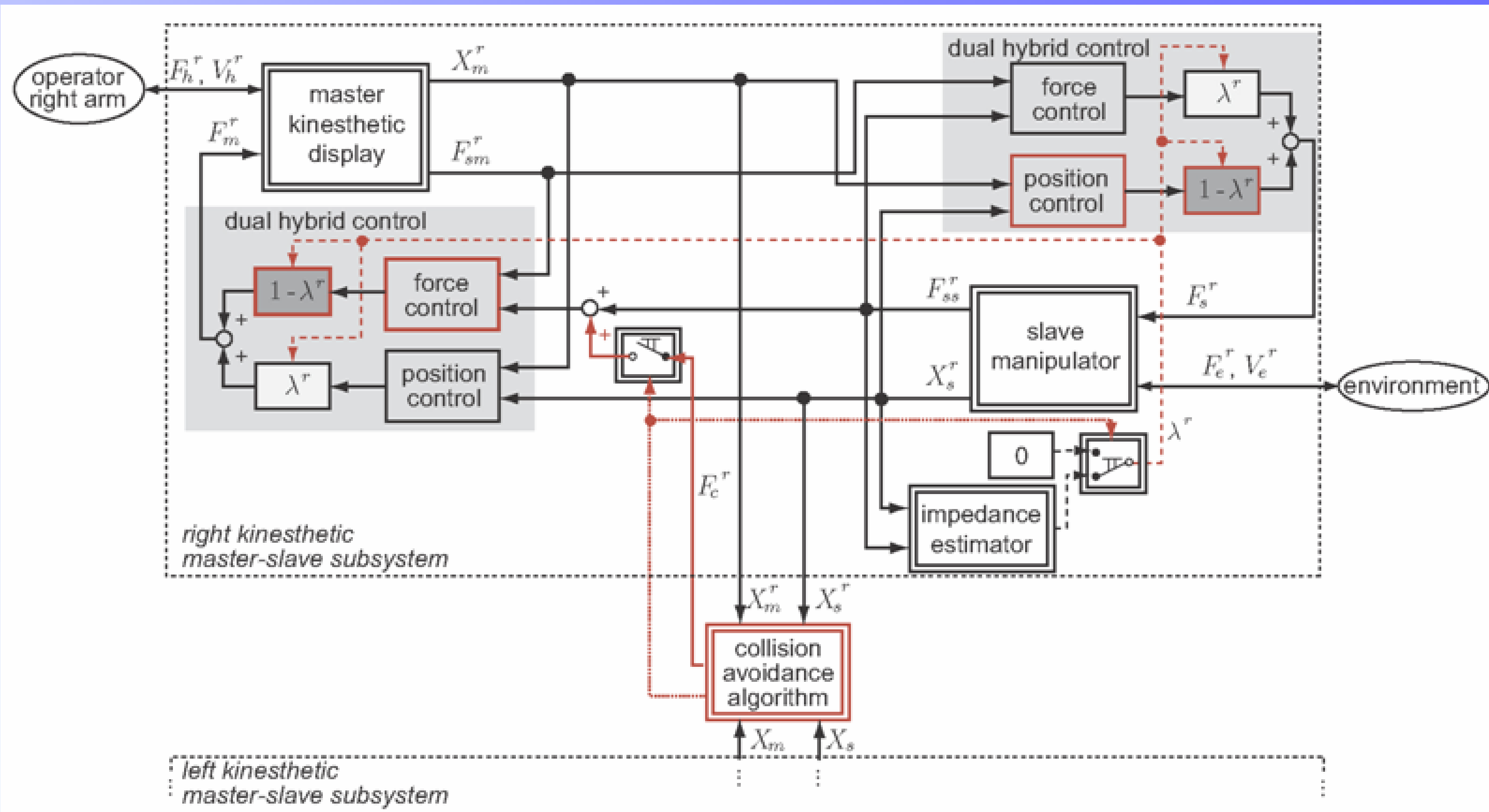
Collision Avoidance, cont‘d



- collision avoidance measures override mode adaptation:

➔ force controlled master & position controlled slave

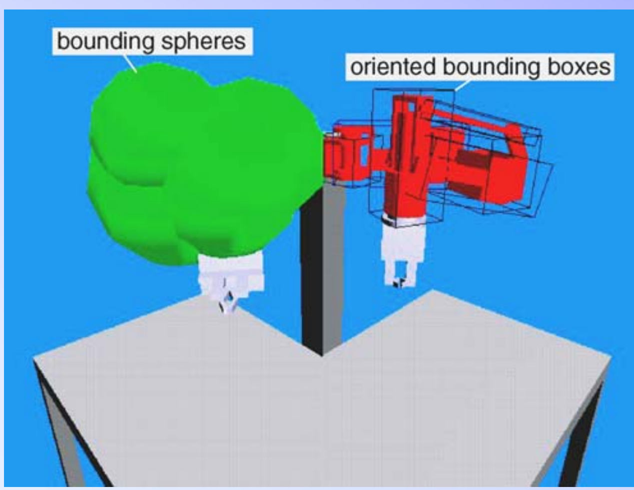
Active Manipulator Collision Avoidance

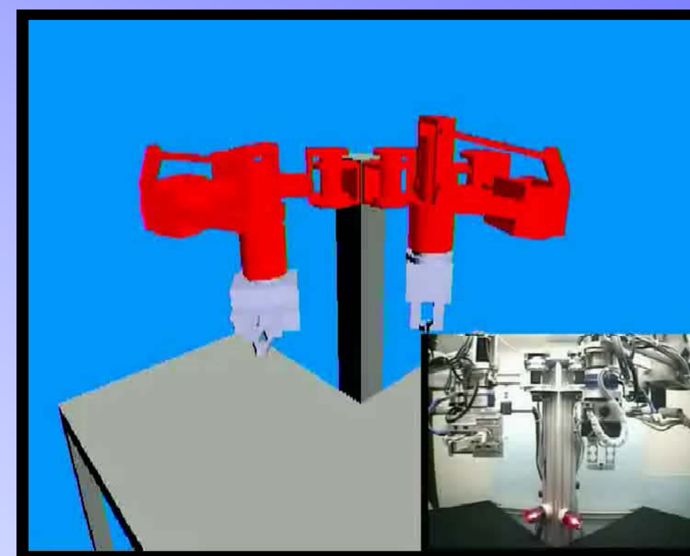
Requirements:

- collision prediction
- active collision avoidance

➔ Augmented force feedback & virtual force arrows in video images

Prediction algorithms: model-based



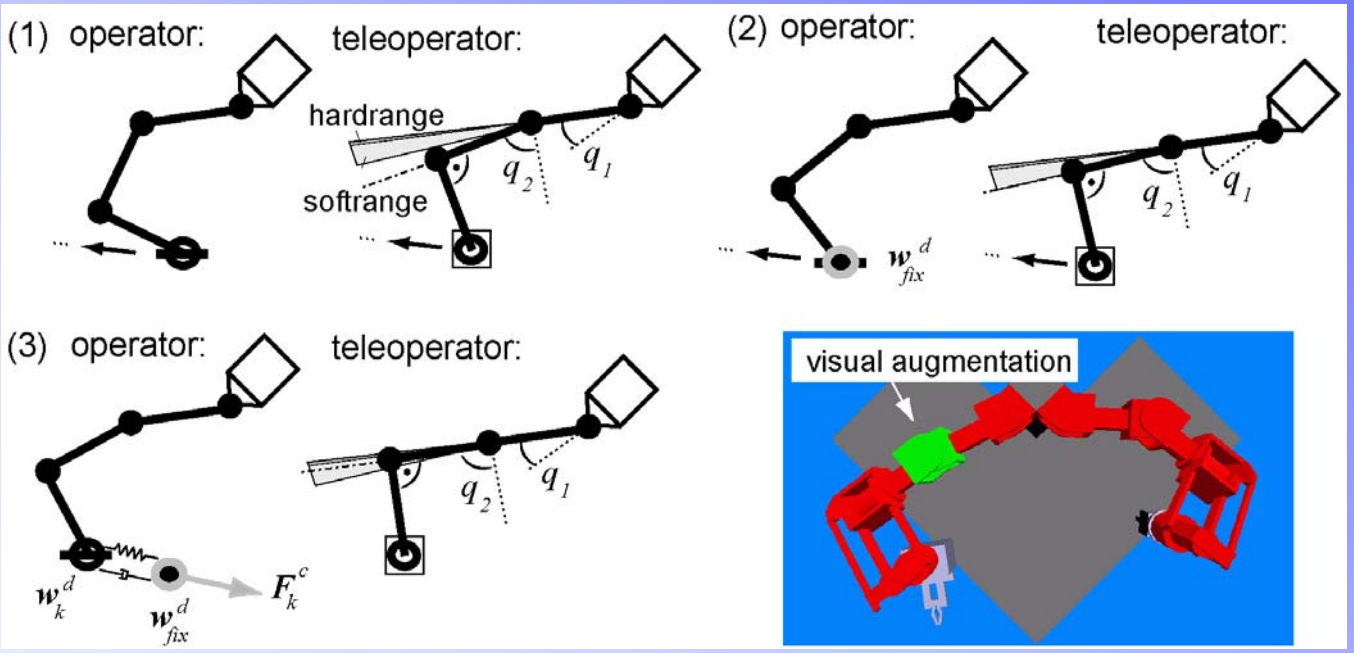


Computation of augmented forces:

- employing virtual spring-damper systems

Manipulator Workspace Penetration Avoidance

Workspace penetration by visual and haptic augmentation



- force computation:

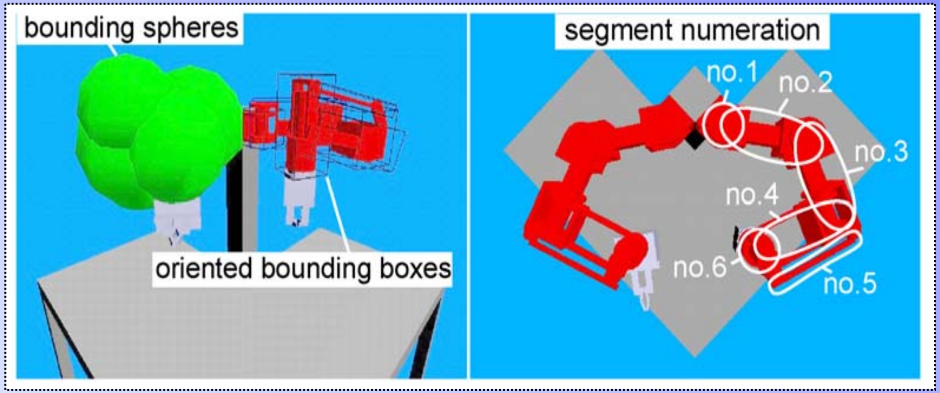
$$\boldsymbol{d}_k = \boldsymbol{w}_k^d - \boldsymbol{w}_{fix}^d$$

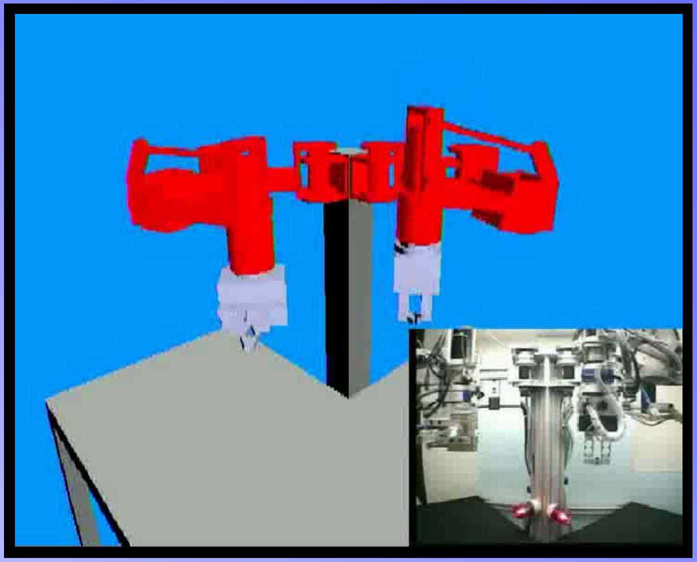
$$\boldsymbol{F}_k = \begin{cases} c_f \boldsymbol{d}_k + c_d \dfrac{\boldsymbol{d}_k - \boldsymbol{d}_{k-1}}{T_0} & |\boldsymbol{d}_k| > |\boldsymbol{d}_{k-1}| \\ c_f \boldsymbol{d}_k & |\boldsymbol{d}_k| \leq |\boldsymbol{d}_{k-1}| \end{cases}$$

- if hard-range reached, all telemanipulator joints are fixed!

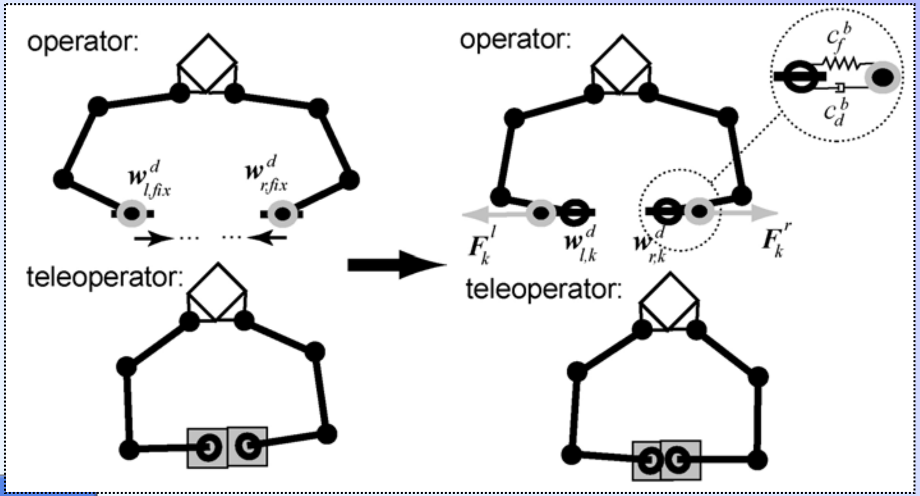
Active Manipulator Collision Avoidance

Collision prediction





Collision prevention by force feedback



- force computation:

$$\boldsymbol{d}_k = \boldsymbol{w}_k^d - \boldsymbol{w}_{fix}^d$$

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Evaluation in Cooperation with Experts from German Armed Forces

Telepresent Disposal of Fragmentation Mine

Operation in remote environment

Some Experimental Findings

- demining task executed by 20 experts

Type of task execution	Time
manual (deminer‘s training)	60 s
remote *demining:*	
▪ novice operator	800 s
▪ trained expert	< 400 s

- efficient (7 : 1) and realistic support by HTP system
- activation of limbs experienced as being “natural“

Verbal statements from experts involved in evaluation:

- „ .... use of both hands for remote demining is highly useful “
- „ .... force feedback provides reliable impression of direct operation at the mine “
- „ .... parallel force feedback at finger and wrist is experienced as a consistent overall force perception “

Activation of Limbs ?

- 20 subjects operated manually, 20 other teleoperated
- subjects express perceived limb activations by percentages

SUBJECT'S DISTRIBUTED FORCE PERCEPTION AT THE LIMBS

contact forces	*manually*		*teleoperated*		**grasp forces**	*manually*		*teleoperated*	
distribution [%] at	$\bar{x}$	σ_x	$\bar{x}$	σ_x	distribution [%] at	$\bar{x}$	σ_x	$\bar{x}$	σ_x
shoulder	24.3	19.3	18.3	19.6	fingertip	46.8	15.0	47.5	21.7
elbow	21.3	16.1	21.3	16.3	phalanx	31.5	16.1	36.0	14.6
wrist	23.8	15.8	25.8	13.4	palm	8.5	8.8	6.9	8.8
finger	30.8	17.6	34.8	19.5	wrist	13.3	12.5	9.6	8.1
χ^2 **-test**		0.54		(0.760)	χ^2**-test**		0.49		(0.785)

No statistical significant difference between manual and teleoperated task execution!

➔ Realistic force feedback !

Conclusions

- EOD may benefit from adoption of available (bimanual haptic) telepresent control approaches
- Stability and transparency by structure adapting control architecture
- Active manipulator collision avoidance
- Encouraging results from evaluation with experts

Next steps

- Attach two-arm manipulator to mobile platform
- Extend maneuvrability to >4 DoF arm motions
- Replace two-jaw grippers by multi-fingered (≥3 fingers) hands
- Optimize interconnection and device control algorithms for the case of non-neglegible communication delays

The End