





















mark in sensing the synthesized reaction. The gear must be low back lash type in construction else it introduces a dead band in operator input around ‘0’ condition in operator input which occurs in condition of restart. It is dealt with in a later section. Experiments in this work have used non-gearred configuration.

*(ii) Compactness and energy efficiency*

Operator interface in real systems need to generate high force-feedback only at contact with unapproachable object as an unusual condition. The infrequent need for high force on operator hand is met by using torque controlled motors with moderate continuous duty rating but intermittent high (up to 300%) torque delivery (fig.9a,10a). The motor and controller combination should be energy efficient [18][19][20] for ensuring compactness and achieving low inertia of overall assembly.

*(iii) Tunable force exertion*

For RP conversion to ‘force-on hand’, the servo motor and controller combination is configured in ‘torque-mode’ and operating sensitivity is designed as illustrated in figures 9 and 10. For example, choosing (I) permits rated torque generation only in entire piston stroke and (II) sets use of 50% range for proximity zone and 200% torque on object contact. Type (I) is suited for manipulated objects while (II) and (III) are suited for non-contactable objects. Type (III) offers coarse force feel in vicinity and rigid opposition on contact and serves best with high torque motor (fig.10) for obstacles and fixtures in workspace.

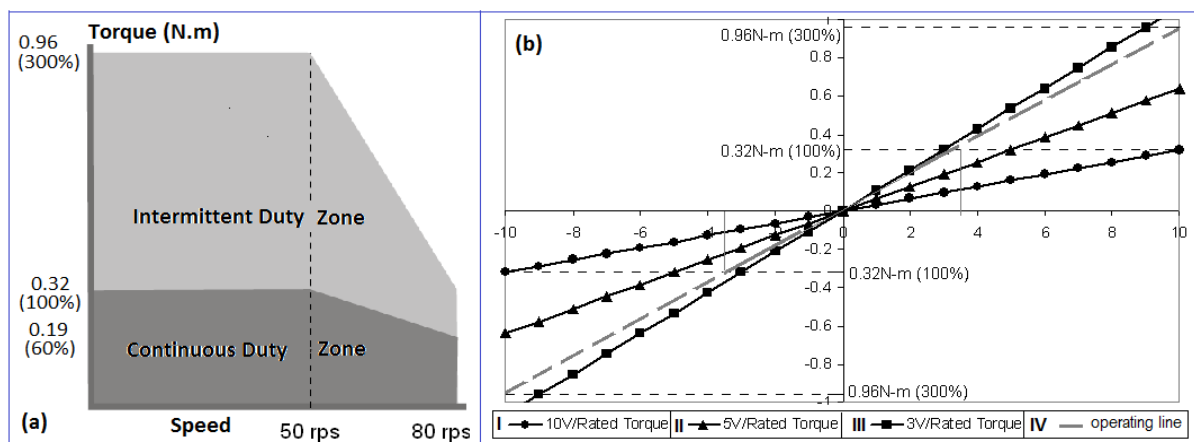


Figure. 9 a:  $\theta$  axis command Voltage-Torque Characteristics. b:  $\theta$  motor characteristics in torque control mode

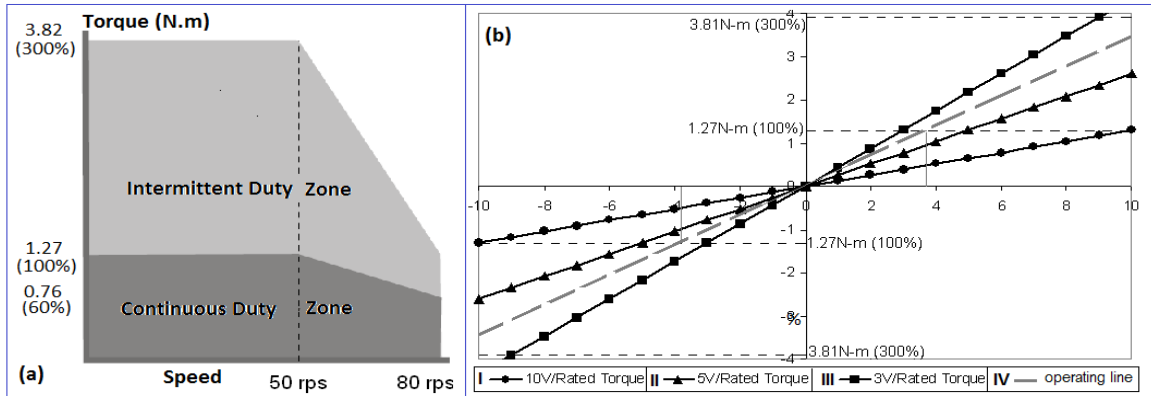


Figure.10 a:  $\theta$  axis command Voltage-Torque Characteristics. b:  $\theta$  motor characteristics (torque control mode)

(iv) The experimental Active Joystick ‘AJS’

Active joystick (AJS) has been formed using 100 W motor on  $\theta$  axis and 400 W motor on  $\phi$  axis. Though  $\phi$  axis has increased inertia relative to 100 W motor, it is less than that of a motor-gear combination and has zero back lash thus eliminating all problems attributed to geared- axes . Axes are adequately counter -balanced. As a consequence the force felt by

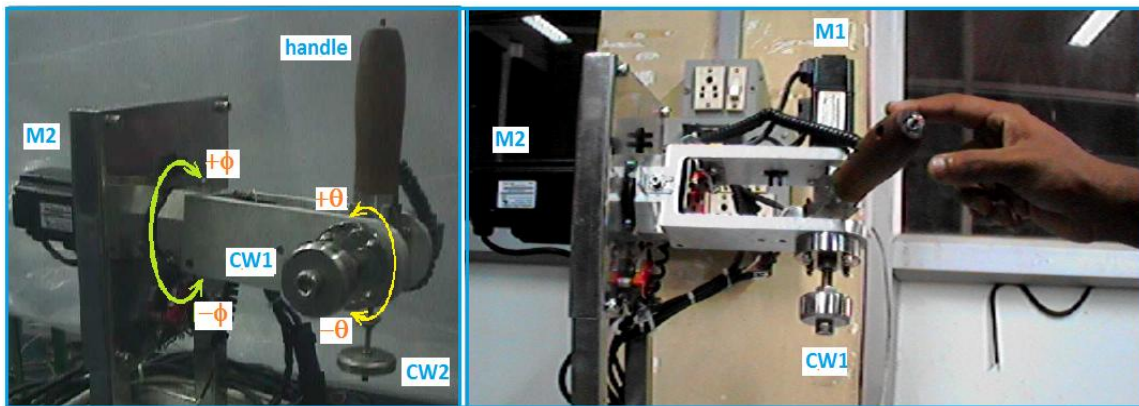


Figure. 11 a (left): The Active Joy-Stick built in laboratory. b: Force feel on operator hand

the hand (fig.11) is purely owing to the motor torques only. The  $\theta$  axis has 0.32 N-m torque capability up to 50rps with torque constant 0.36N-m/A. and  $\phi$  axis has torque 1.27 N-m up to 50rps with torque constant 0.49N-m/A. Experiments were done for both exclusively. The AJS developed in laboratory (fig 11) employs light wooden handle and aluminum chassis to keep inertia low and uses counterweights to attain balance. Motor at joint without gear is the key feature. The operating characteristics are set in experiments here along the dotted operating lines (fig. 9b.10b).

## V EXPERIMENTAL PERFORMANCE

An experimental set-up is built using a tele-controlled set up that uses 5 DOF robot [21] of Cartesian type (fig.12a). The REE can be oriented in space by rotations in two mutually orthogonal plane and located by 3 axis Cartesian positioning in a workspace of size 1000x1000x600mm. The robot and associated control set-up is equipped with joint position and velocity sensing electronics [22]. The servo system executes all motions with commanded speed in closed loop controlled manner [23][24]. During a single axis motion execution, joint position and velocity are sensed and computations (fig 7b) are done to form RP as per model. RP signal are applied to AJS for torque generation (fig 12b). The problem of placing aforementioned model in REE's motions path while approaching a body is solved by associating  $\rho$  values in workspace model (fig. 7a) which is discrete position representation in the 3D Cartesian work space analogous to 'pixel' in 2D image representations and referred as volume element or 'voxels'. The voxels also hold local property of this tiny space. The property can be of varied types and their use have yielded fast response in diverse methods like hit detection and robot path finding in 3D space [25] [26]. A solid cube placed in workspace appears as in figure 7a. In 3D space of the robot 'Z' (height) is kept fixed at 300 mm,  $\gamma_m$  values in the 2D plane are assigned by treating it as 2D array and REE motion is permitted in this plane. In experiments, X motion occurs at controlled speeds along constant 'Y' within coded zone.

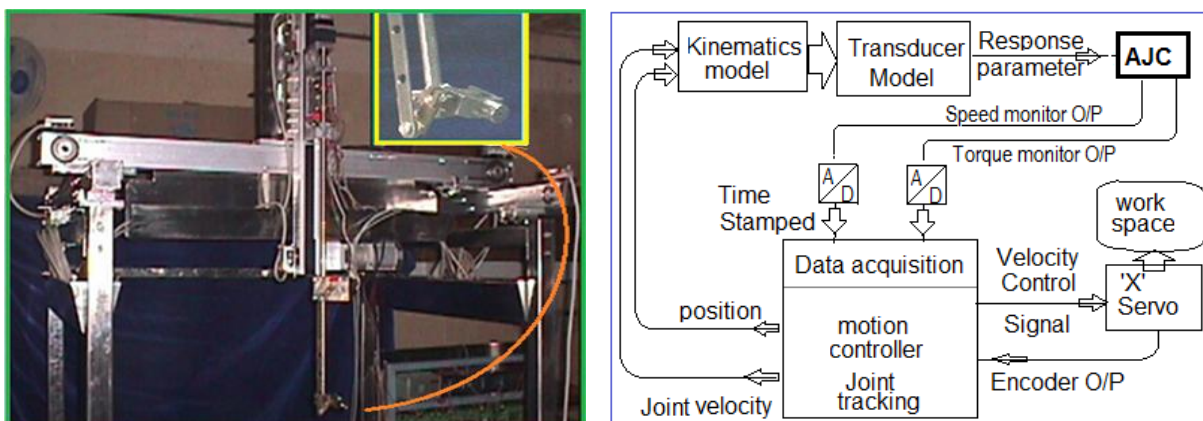


Figure (left) 12a, 5 DOF Cartesian robot experimental set-up. Figure (right) 12b. A single axis test setup in the experiment. AJS is joystick controller, time stamping is used for unified temporal data referencing.

### A. RESPONSE PARAMETER 'RP' GENERATION:

In the experiments, slave motor (5DOF robot) worked on velocity control mode. Velocity control signal to the controller was formed by 14 bit accuracy D/A output and updated at

100 Hz. Shaft encoder tracking was achieved by the slave joint controller and time stamped position was acquired. For high speed approaches, the object surface was used as data coded limit and real object was removed for avoiding inadvertent damage during experiments, .

(i) Regular size ‘G’ based model

The probe robot arm was moved along a fixed ‘Y’ at different constant velocities which were sensed by the robot joint sensors in real time. The ‘F’ values generated by the model are shown in figure 13. ‘RP’ developed by the system for same conditions but constant accelerations and constant deceleration are shown in figure 13b and 13c.

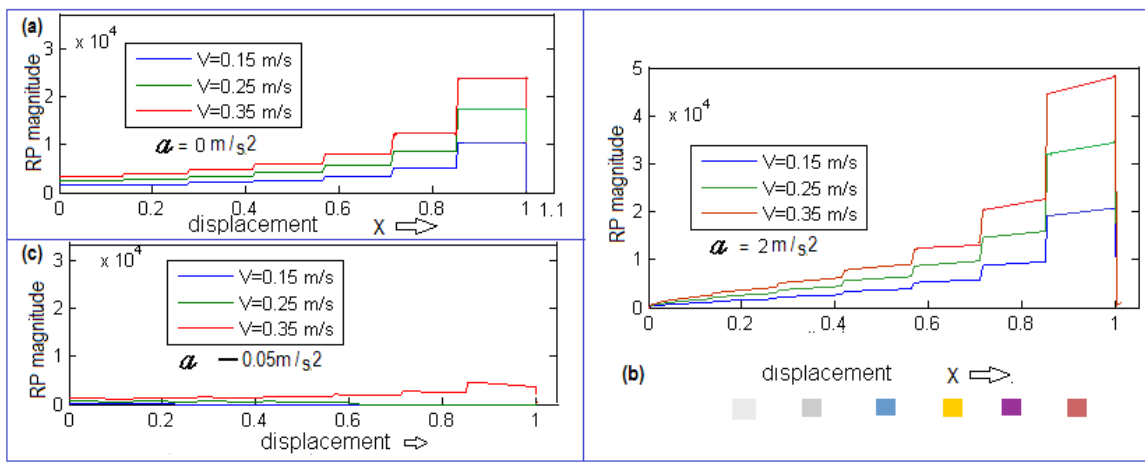


Figure 13 ‘RP’ generated at different seeds of REE for transducer model coded as per (10)

(ii) Effect of variation of ‘gap’ between bypasses

The parameter ‘G’ i.e. gap(fig.5a) is mapped as ‘k’ (integer) numbers of voxel of length ‘ $Vx$ ’. Therefore ‘k’ is scale factor between real workspace and model. For  $k=2$ , fluid resistance  $\gamma$  forms an array that appears as

$$\gamma_1, \gamma_1, \gamma_2, \gamma_2, \gamma_3, \gamma_3, \gamma_4, \gamma_4, \dots, \gamma_{(n-1)}, \gamma_{(n-1)}, \gamma_n, \gamma_n \tag{10}$$

The profile is depicted by different color code in figure (14 a) and is repeated for a set of Y values for facilitating single axis motion along X axis. If value of gap ‘G’ is reduced then ‘k’ reduces. Lowest value can be  $k = 1$ . The coding is shown in figure 10a and effect is depicted in figure 11b. The advantage of narrow gap is evident in closer vicinity where a responsive operator reduces speed causing REE slowing down but bypasses being nearer still senses slowdown owing to frequent change of  $\gamma$  rather than change of ‘v’ which may not be appreciable over short travel. An interesting way of enhancing closeness perception is to have gap ‘G’ of different sizes. At periphery of vicinity G can be longer and close to object it can be reduced. For such case the  $\gamma_m$  coding for the same part is as shown in figure 14b. The

resulting ‘RP’ is shown in figure 16c. As REE approaches closer to the object the transducer produces more frequent ‘RP’ change giving feel of increasing proximity by increasing frequency of step changes on AJS.

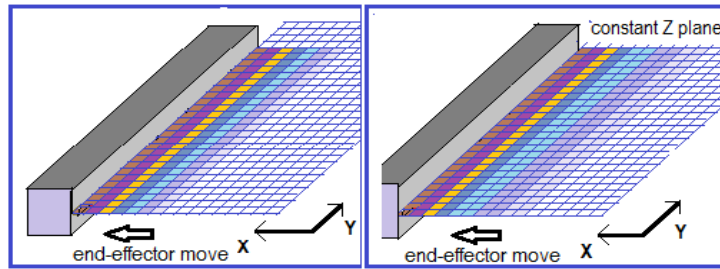


Figure 14a. Coding for narrow ‘G’; Fig. 14b. for unequal gap ‘G’

**B. Performance of the transducer**

*(i) Performance for approachable part*

The servo controller of AJS motors provide instantaneous torque proportional signals at monitoring output. For a nominal holding position at 75mm from the AJS shaft, the force appears as in figure 15 for REE motion executed by controller at zero acceleration, constant acceleration and constant deceleration. Tests with narrow regular G as well as varying G too have been conducted (fig16).

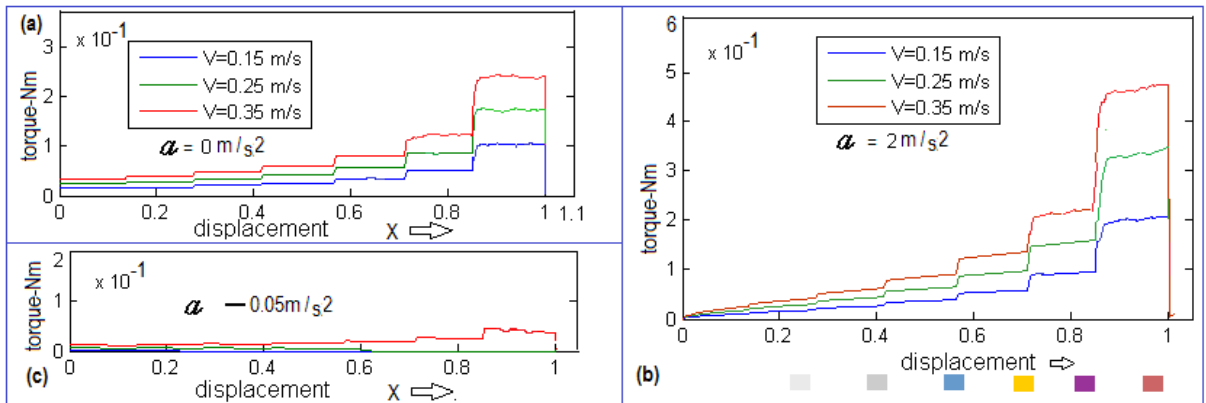


Fig.15 Performance of transducer ( $\theta$  axis) for constant G and fixed, accelerating and decelerating motions.

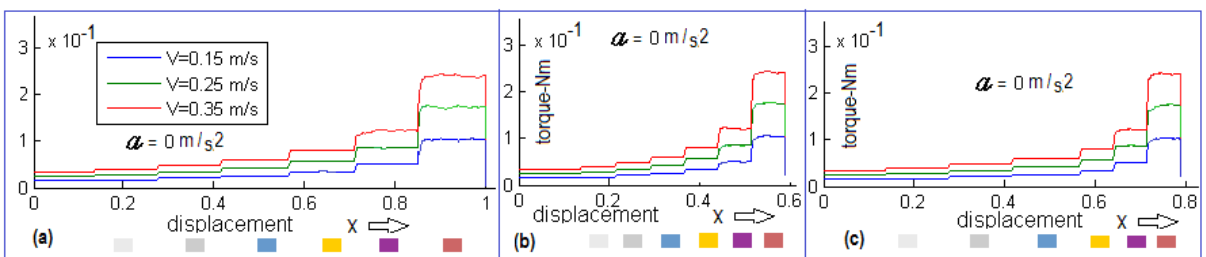


Figure 16. Effect of changing ‘G’ on force feedback. a; regular gap with  $k=2$ , b; regular gap with  $k=1$  and c initially  $k=2$  and later  $k=1$

The AJS produces stepped force opposing operator hand which increases in magnitude with advance of REE towards object. For higher velocity of approach, at same relative distances from object surface it produces higher force magnitude step. On frequency scale the faster move generates increasing frequency of steps. A design with lower  $G$  near cylinder end offers relatively faster step occurrence at low velocity too and enhances perception of approach to object more effectively.

(ii) *Performance for un-approachable part*

An unapproachable part is modeled by coding the last layer adjacent to a part (red in figure 17a) with an additional attribute whose effect is to consider 'F' as a predetermined high value rather than as computed by (7). The  $\gamma_m$  coding for unapproachable part along with blocking layer and F generated for it appear in figure 17a and 17b. Note that such block may cause shock on AJS for fast move but the preceding high opposition by AJS actually prepares the operator for the situation. For a slow move stepped force at block is manageable. Progressively reducing  $G$  in design can restore frequency based feel for slow speed too.

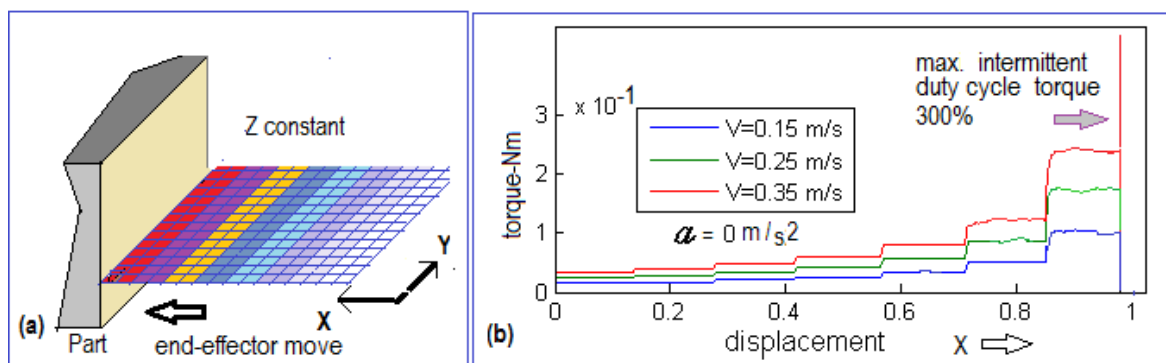


Figure. 17 unapproachable part (left) and F generated for it (right)

The 'RP' in experiments produced perceivable opposition force to operator's hand placed at nominal distance of 75 mm from rotation axes in manner expected using  $M_1$  on 100% dynamic torque range for approachable objects. For non approachable objects, rigid opposition at conditions equivalent to body contact was not felt adequate at operator's hand using  $M_1$ . Operator, if not cautious can force through the opposition. However using  $M_2$ , perceivable rigid opposition could be formed within 88% of torque range. For constant speed move, generated by computer controlled servo, appreciable stepped changes in force were produced for low speeds when high torque gains were set. But for speeds above 0.3 m/sec. force was high enough to push back inexperienced operator. Response parameter developed here works well (table 1). Individual's sensitivity being different, range tuning is desirable.

Table 1: Force Output Performance Of AJC In Intelligent Transducer.

Motor	Mode	Control signal (volts)	Torque Usage	Experimental observation
M1	Vicinity at normal speed	0 – 3.6(+/-)	Normal demand	Effective force feedback dependant on vicinity.AJS operation is low inertia, quick response. Transducer action very good. Well suited for delicate manipulation.
	High Velocity	3.6 - 8 (+/-)	Overdrive 250%	
	Contact	10.0 (+/-)	Full overdrive (300%)	Distinctly felt contact opposition, operator caution must for not breaking toque limit.
M2	Vicinity at normal speed	0 – 3.8(+/-)	Normal demand	Effective force feedback dependant on vicinity with wider force range. Transducer action very good. AJS feels heavier on hand
	High Velocity	3.8 - 7 (+/-)	Overdrive 200%	
	Contact	10.0 (+/-)	partial overdrive (250%)	Rigid opposition at contact, robust operation against operator error. Well suited for obstacles and non contactable objects

The participating experimenters were permitted to set ‘RP to force ratio’ by adjusting torque gain of M1or M2 as per their sensitivity. All experimenters perceived the approach phenomenon in spite of not being allowed to see the robot and workspace

## VI IMPROVEMENT OF OPERATING INTERFACE

The RP maintains passivity in operator controlled motion loop as stopping motion causes  $F=0$  condition and operator can hold the robot at place in vicinity of a part. However the operator should continue to perceive vicinity in some way else sudden motion can be initiated by him/her in absence of vicinity feel and in systems having limited bandwidth for feedback, contact with considerable mechanical impact can occur. The AJS formed for converting RP to real force perception using toque motor may have a drawback. For developing significant force on operator hand the torque motor needs to be bigger and hence result in low or at best moderate bandwidth of the force conversion from RP. Solution lies in using  $\gamma$  (8) in an ingenious way to form multimode interface at master.

Motivated by multimode interface [28] we form it by feeding tones to a audio speaker based on  $\gamma$  (figure 13). While the RP is used for developing opposing torque by AJS,  $\gamma$  dependent variable frequency audio tone makes the operator aware of relative closeness to the object even when REE is kept standstill by operator.



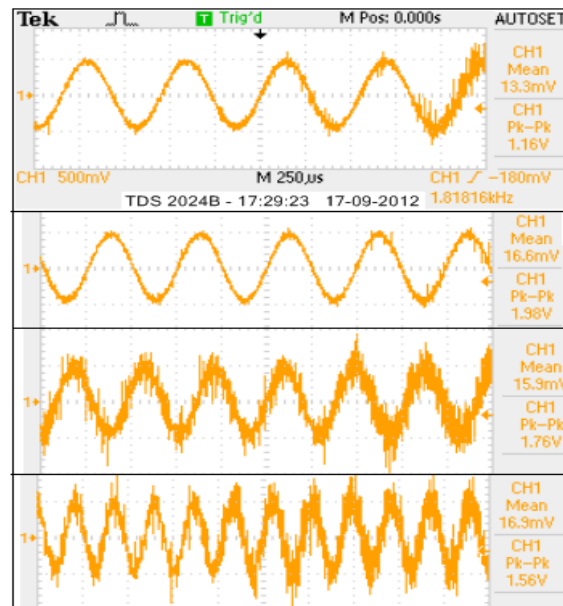


Figure. 13 Audio tone fed to speaker amplifier.

Top to bottom; tones at locations approaching object irrespective of speed of approach.

## VII CONCLUSION

Efficacy of the synthesized transducer lies in its capability of distinctly different response creation for manipulated and non approachable objects like workspace construction features and obstacles defined by the task definition in a structured remote work environment. Yielding opposition to operator as well as rigid opposition is feasible in the transduction scheme. The vicinity activation model effectively supports intelligent human-machine interface formation.

The characteristic is tunable by tweaking independently behaving parameters. Spatial variation of bypass gap 'G' in non uniform manner can be used to cause more frequent change in the response parameter at closer vicinity and offer improved perception of approach to a body by temporal changes of force which are inherently immune to background noise arising from velocity sensing errors. This illustrates re-configurability of the model. The model is predominantly software implemented and so is highly amenable to automated formation for complex workspaces created by CAD modeled objects. Automated formation has been addressed [29] by imparting motion resistance property in the surrounding space around the modeled version of the real object. This gives a strong sense of relative object approach which is more effective than vision based approaches as a view by itself needs to be augmented with contextual interpretation aid [30][31]. Verification of the method is possible by using a laboratory version slave robot instrumented without interconnect

encumbrance similar to that devised for wireless monitoring of utilities [32] as the wireless sensor networks are evolving with better functionality [33]. The transduction method developed here can also work with interfaces such as the electro-hydraulic type actuators [34] for heavy duty applications. Though the audio feedback is produced in different perception domain, fusion of effects happens in operator brain and the perception is effectively enhanced. The method is attractive for tele-managed probing as well as operator training systems for tele-control.

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