Saw Blade Chatter Detection and Correction–Developing the Smart Tooling Concept for Remote Manipulation*

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Abstract—*Cutting of metal structures is a regular need in decontamination and decommissioning (D&D) of contaminated Department of Energy facilities. Plasma torch cutting is efficient, but there are many cases and situations where it is not appropriate. Sometimes the fire hazard cannot be tolerated; sometimes it is more of a contaminant dispersal issue. Circular saws, band saws, and reciprocating saws are often the necessary tool of choice. Sawing is a complex action that is difficult to execute with remote manipulation without extensive task-specific fixturing of the tool to minimize blade chatter and binding. Extensive fixturing leads to the requirement for multiple tools for each minor variation of the task. This drives up the cost of remote tooling for a given D&D large-scale task, generates clutter and tool storage issues, impacts tool reliability due to complexity, and increases the required spare parts. This paper presents an investigation of the saw tool chatter issues, ways to detect chatter for the control system, and compensation methods that lead to a new approach to tooling use with remote manipulation–smart tooling.*

I. BACKGROUND

It is typically difficult to saw with servomanipulators without extensive fixturing. The saw blade must remain orthogonal to the work piece cut in at least two axes, and the feed rate must be appropriate for the material and the condition of the saw and saw blade. If not, jamming, binding, and chatter may result, leaving the operator with the need to restart a new cut or attempt to pick up where the original cut left off; either is a time-consuming and fatiguing operation. One of the more interesting issues is that the manipulators typically used in remote operations are susceptible to excitation and oscillation when using reciprocating saws due to their compliance and particular mechanical bandwidth. Under binding conditions, the saw slows down until the cutting oscillations are in the frequency range of the response of the manipulator; the manipulator then oscillates with the sawing motion instead of the saw blade oscillating on the work piece stopping the cutting action. It has been much easier to apply band saws and circular saws to remote manipulation for this reason; however, circular saws have the most difficulty with blade binding, and band saws have the problem of dealing with retracting a flexible blade back through the cut once a cut has been made. Reciprocating saws would be the most versatile and robust remote maintenance saw tool if the chatter and binding problem could be solved, and any improvement to remote cutting operations could significantly decrease the cost of remote decontamination and decommissioning (D&D) operations. The intent of this work is to start with a band saw and migrate to a reciprocating saw.

The technique presented in this paper uses a tool-mounted accelerometer to detect chatter in sawing action. The sensor signal is filtered to separate the high frequency components from the low frequency components; the algorithm that has been developed and is being applied to sawing examines both the frequency content and amplitude of the two signals to generate a probability of the existence of "chatter" (more oscillation in this specific case). High and low pass filters are applied to the same raw real-time signal to split it into components. The variance of each of the signals is then computed, and a ratio of high to low frequency signal power is established. One of the more difficult tasks is to decide on the breakpoint between what constitutes high and low frequency content. This is based on both empirical studies of the saw in question and the sawing operation in general and on the bandwidth of normal human input in teleoperations.

The manipulator itself cannot compensate for the tool chatter due to its bandwidth limitations. In the initial testing, when saw chatter is detected, the feed rate of the saw (via the manipulator) is modified to eliminate chatter. Future studies will investigate compensation more thoroughly, increase the sample rate, using dynamic compensation. Final investigation and implementation of this technique is currently in progress in the telerobotics laboratory at the University of Tennessee at Knoxville (UTK) on the robot task space analyzer (RTSA) robot system.

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The sense of the need for smart tooling-based telerobotics grew out of Oak Ridge National Laboratory's (ORNL's) participation in the D&D of the Argonne National Laboratory Chicago Pile #5 (CP-5) research reactor in the 1990s where the reactor vessel had to be sectioned and removed remotely using mechanical cutting by D&D workers unskilled in remote operations. D&D workers used a dual-arm manipulator system, shown in Fig. 1, and circular and band saws, shown in Figs. 2 and 3, to cut up the reactor vessel and associated hardware. Extensive lessons learned during this activity led to the creation of the smart tooling concept.[1]

Fig. 1. Dual-arm work platform at CP-5.

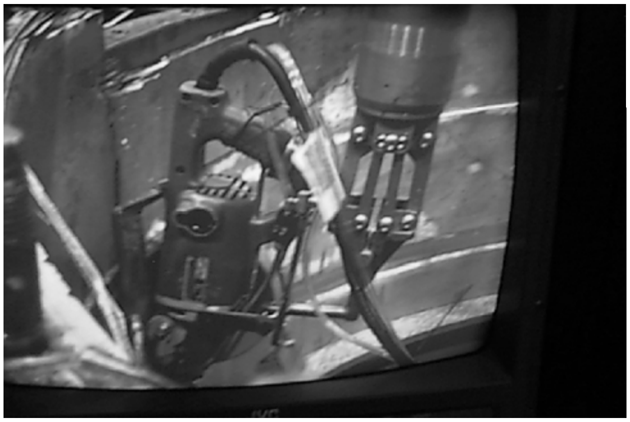

Fig. 2. Remote cutting using a circular saw.

The initial work in smart tooling, shown in Fig. 4, was done at ORNL using a plasma torch tool to cut structural steel components to meet a need for sectioning process equipment.[2] The tooling and techniques developed as part of this exercise extend these concepts to remote sawing. While this particular implementation uses sensing only, the full concept integrates both sensors and actuation to provide the added functionality that the manipulator alone cannot provide. This is different from the traditional remote systems "set-in-place" automated tooling designed to be delivered to one specific task by remote manipulators for execution. A smart tool package is designed to work in conjunction with, rather than to replace the manipulator, to provide the most cost effective augmentation to perform the task. The full teleoperation-oriented smart tooling approach assists the operator with additional sensors and actuators at the end-effector tooling package.

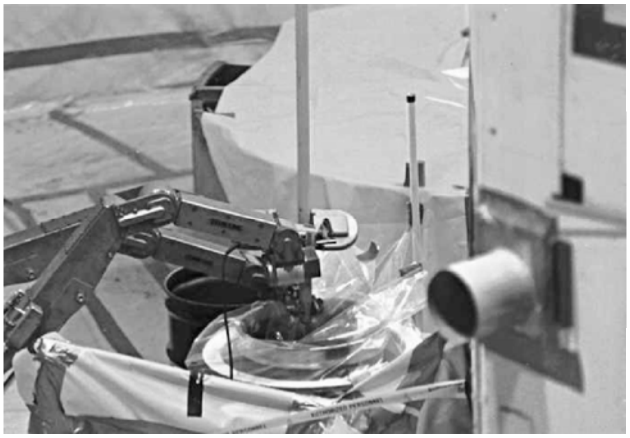

Fig. 3. Remote cutting using a band saw.

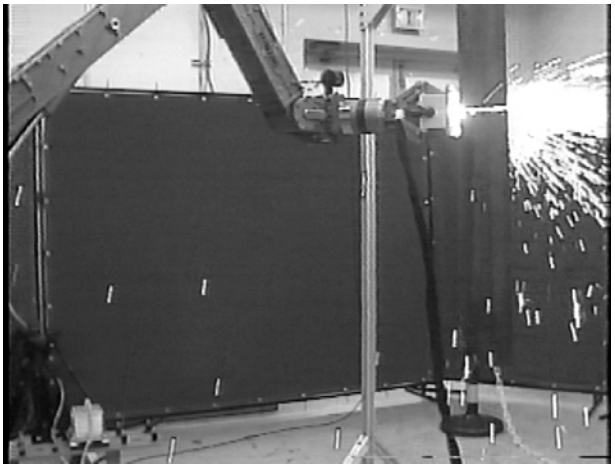

Fig. 4. Plasma torch smart tool operation at ORNL.

The core elements of the concept include (1) a traditional robotic pick and place capability for tooling selection and return, (2) high fidelity teleoperation to manage positioning of the end-effector tooling and to provide the best teleoperation possible for execution of tasks where no tooling automation is practical, and (3) a series of tools, each with a family of tool behaviors for automatic execution of tasks common enough to warrant special tooling. In its ultimate form, the operator selects the task that he wishes to execute via the operator interface. The system then automatically picks up the correct tool for that task and returns to a home or ready position. The operator then teleoperates the manipulator's end-effector to the target task (such as section cut of a horizontal pipe with a reciprocating saw). The tool package behaviors' sensors acquire the pipe in the proximity of the operator's preference making assumptions based on a priori task behavior configuration and takes control of task execution from the operator. Once the task is completed, control of the manipulator is returned to the operator who can then choose to perform additional tasks with that tool or to automatically return the tool to the tool stand. While there are some shared control components to this scheme, it is primarily a variation on traded control with three components: teleoperator operator, pick and place robotics, and sensor-based behavior-based robotics.

II. CHATTER DETECTION

Machine tool chatter was a topic of concern for most of the 20th century; improvements were made, but much has yet to be understood and done.[3,4,5] Saw blade chatter received much less attention but there was some research done in the past few years.[6,7,8] Liang et al. made the most significant contribution to this effort with their description of chatter detection and suppression techniques.[9] Machine tool chatter can be detected by the equipment operator via characteristic sounds and surface finish, and the results of saw blade chatter can be physically seen in oscillations of the entire saw at much slower speeds than the actual tooth chatter. While this motion is secondary to the forces caused by the chatter of individual saw blade teeth, the same techniques can be applied to automatically detect chatter, necessary for any automatic compensation. The compensation technique particularly chosen requires that a threshold be established that indicates chatter or oscillation, and this must be done from empirical data collected experimentally using accelerometers. This means that the algorithm must be tuned for different tools. Once this threshold has been established, the existence of chatter can be established by a ratio of variances[9]:

$$R = \left[\frac{\sigma_{low}}{\sigma_{high}}\right]^2 = \frac{\sigma_{low}^2}{\sigma_{high}^2} \qquad (1)$$

where σ_{low} is the variance of the accelerometer signal low frequency components, and σ_{high} is the variance of the accelerometer signal high frequency components. When R<<1, then the tool is into a chatter mode; however, the exact threshold to define how much less than one the ratio must be to indicate chatter must be established experimentally on a case-by-case basis.

The variance is defined by:

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \qquad (2)$$

where:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (3)$$

Liang et al.[9] also suggested that varying the "spindle speed" of the tooling could move the excitation away from the natural frequencies of the particular cutting process thereby alleviating chatter. This prompted an experiment with the band saw spindle speed that proved valuable for the physics-based component of this effort.

Several decisions have to be made before implementation of the algorithm specified in Liang et al.[9] Since testing has not been completed due to funding limitations and scheduling problems, these decisions will be subject to change as a part of the test and debug process; however it was necessary to establish a baseline to initiate testing. The most important selection is that of the cutoff between the high and low frequency components; another is the buffer size for the variance calculations. There are also the capabilities of the RTSA controller to consider since this technique will be integrated into the RTSA Linux-based controller. The initial control loop rate of the Linux controller is limited to a maximum stable sample rate of 128 Hz which means that any signal higher than 64 Hz cannot be properly sampled. Further, the rate of purposeful task motion in human remote operations is down in the 1 Hz or less range, and the tool oscillation of interest is in the range of "several" hertz. Therefore a preliminary cutoff frequency of 2 Hz was chosen for the design. The variance calculation buffer size was selected somewhat arbitrarily as 128 elements for initial testing. All preliminary values are subjective and subject to change based on testing.

The chosen technique dictates the use of accelerometers to capture the presence of chatter. UTK supplied a compact all-in-one 3-axis +/- 2G accelerometer from Jewell Electrical Instruments along with vendor calibration data. The 3-axis accelerometer was mounted in a custom-designed interface block along with an ATI Industrial Automation 6-axis force/torque sensor procured by UTK for more general experiments unrelated to this project but which impacted the sensor system design. The design of the tool block was such that it facilitated pick up by the Schilling hydraulic manipulator used by the UTK RTSA and also that it facilitated adaptation to different tools on the tool plate end. The tool and sensor "smart" tool package is shown in Figs. 5, 6, and 7 broken down into the sensor/grip block, the saw fixture component, and the assembled tool. The specific design, based on the ORNL plasma torch experimental design, permits the sensor module to be readily adapted to other tools minimizing replication.

The accelerometer signals were connected to an analog input board in the Linux-based personal computer

(PC), and an open source device driver was used to interface it to the Linux operating system. Serious software version and compatibility issues turned out to be a major implementation problem that was totally unexpected.

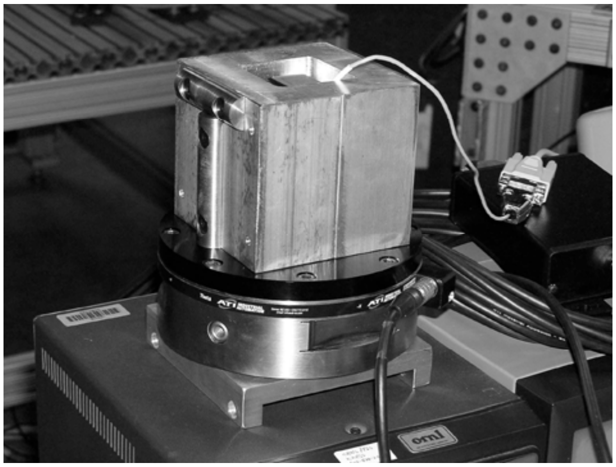

Fig. 5. Smart tool sensor side.

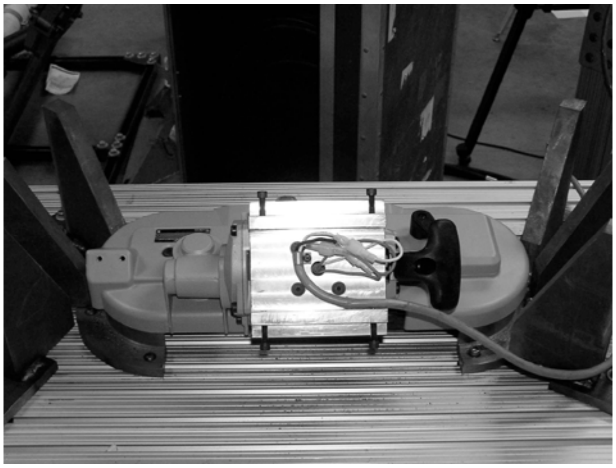

Fig. 6. Smart tool saw side.

The selected chatter reduction technique dictates that the accelerometer signals be separated into high and low frequency components. Standard digital filtering techniques were used to produce the separated signals.[10]

The particular style/format of the digital filter structure selected was the infinite impulse filter (IIR). The advantage of IIR filters is that they are generally more computationally efficient than other types of digital filters, which is useful for real-time implementation. Disadvantages include greater design difficulties and greater sensitivity to stability issues, round-off errors, and signal nonlinearities.[10] In order to minimize stability and implementation concerns, the choice was limited to second order filters for both the high pass and low pass blocks. Higher order filters produced extremely high gain values in the design investigation phase that would have been a significant implementation problem. A block diagram of the basic filter configuration is shown in Fig. 8.

Fig. 7. Assembled band saw smart tool.

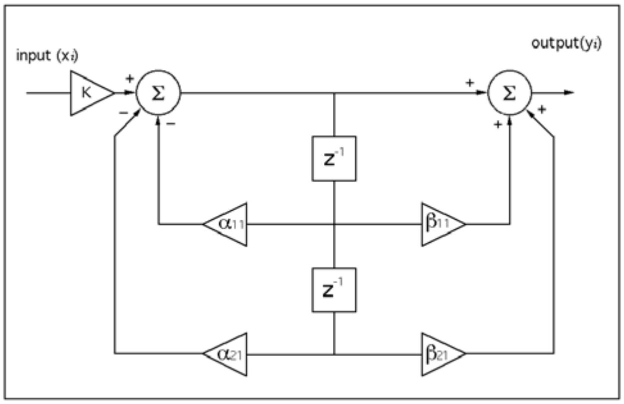

Fig. 8. IIR second order digital filter block diagram, (adapted from reference 10).

The digital filter is assumed to have the form[10]:

$$H(z) = K\prod_{n=1}^{N} \frac{1+\alpha_{1,n}z^{-1}+\alpha_{2,n}z^{-2}}{1+\beta_{1,n}z^{-1}+\beta_{2,n}z^{-2}} \tag{4}$$

The particular technique for filter design generates *H(z)* from a transformation of a *s*-domain designed filter of the form[10]:

$$H(s) = \prod_{n=1}^{N} \frac{a_{2,n}s^{2}+a_{1,n}s+a_{0,n}}{b_{2,n}s^{2}+b_{1,n}s \_ b_{0,n}} \tag{5}$$

The desired analog/continuous filter *H(s)* is then "prewarped" to the proper cutoff frequency before using the bilinear transform[9] where prewarping and bilinear transform equations are specified as:

$$C_W = \frac{f_s}{\pi}\tan\left(\frac{\pi f}{f_s}\right) \tag{6}$$

where:

C_W is the prewarping constant,
f_s is the sampling frequency of the control system, and
f is the desired cutoff frequency of the filter, and:

$$s = 2f_s\frac{1-z^{-1}}{1+z^{-1}} \tag{7}$$

These equations establish the desired $H(z)$ coefficients given $H(s)$ a, b, and K coefficients as follows[10]:

$$\alpha_{1,n} = \frac{-8a_{2,n}f_s^2 + 2a_{0,n}}{4a_{2,n}f_s^2 + 2a_{1,n}f_s + a_{0,n}} \tag{8}$$

$$\alpha_{2,n} = \frac{4a_{2,n}f_s^2 - 2a_{1,n}f_s + a_{0,n}}{4a_{2,n}f_s^2 + 2a_{1,n}f_s + a_{0,n}} \tag{9}$$

$$\beta_{1,n} = \frac{-8b_{2,n}f_s^2 + 2b_{0,n}}{4b_{2,n}f_s^2 + 2b_{1,n}f_s + b_{0,n}} \tag{10}$$

$$\beta_{2,n} = \frac{4b_{2,n}f_s^2 - 2b_{1,n}f_s + b_{0,n}}{4b_{2,n}f_s^2 + 2b_{1,n}f_s + b_{0,n}} \tag{11}$$

$$K = \prod_{n=1}^{N}\frac{4b_{2,n}f_s^2 + 2b_{1,n}f_s + b_{0,n}}{4a_{2,n}f_s^2 + 2a_{1,n}f_s + a_{0,n}} \tag{12}$$

The technique used to generate the appropriate high or low pass *H(s)* is outlined in Ludeman.[11] For the low pass filter, a normalized analog low pass filter will be transformed to the correct frequency and for the high pass filter, a normalized analog low pass filter will be converted to a transformed high pass filter.

The normalized second order low pass form is:

$$H(s)_{LPF} = \frac{1}{s^2 + \sqrt{2}s + 1} \tag{13}$$

The normalized second order high pass form is:

$$H(s)_{HPF} = \frac{s^2}{s^2 + \sqrt{2}s + 1} \tag{14}$$

These two equations are the starting point for the analog to digital filter transformation using the prewarping equation. Implementation-wise, an analog (hardware-based) low pass prefilter is also necessary for data acquisition and signal processing of the accelerometer signals; the prefilter was designed and installed per standard practices.[12] The future possibility of running the control system at a much higher sample rate will dictate that the filter calculations all be redone, but the procedure is straightforward.

III. CHATTER CORRECTION

Because the mechanical bandwidth of the typical remote manipulator is well within that of the typical saw, pure physics-based techniques, while useful, are not completely workable. Many band saws and reciprocating saws generate oscillations directly in the bandwidth of the manipulator. One way to address this would be to create tools that operate outside of the bandwidth of the arm so that they do not excite undesirable motion. As part of this effort and in accordance with published literature by Liang,[9] experiments were conducted to vary the speed of the reciprocating saw motor by varying the applied voltage with a variable ac transformer. Preliminary subjective measurements were made at normal and at elevated operating voltages (30% over normal) for the handheld reciprocating saw and the band saw. Reciprocating saw tests were run with the manufacturer-recommended blade for the material and cutting circumstances that included a two-inch carbon steel pipe and hand-held operation. At normal operating voltage with the recommended blade, vibration and kickback were significant; the saw was very uncomfortable to use. At the elevated voltage, the reaction frequency was much higher and its magnitude was much lower, making for significantly more comfortable operation and characteristics that would help to minimize manipulator oscillation. An additional interesting note was that the blade was changed out to a more generic task type blade, and the kickback reduced significantly again. It appears that following the manufacturer's recommendations exacerbates the chatter problem in hand-held and manipulator-based deployment. For the band saw, the added torque from the additional voltage appeared to also reduce tendency to chatter, though the benefits were not as obvious as with the reciprocating saw. There will be some longevity issues with running these tools at what amounts to 30% over rated voltage; however robotic operation generally consists of short bursts of use and not continuous operation. Running the tools at a higher voltage to get a higher frequency of oscillation along with higher cutting torque will be used as a physics-based component to the overall chatter compensation technique.

While it would be advantageous controls-wise to have a totally physics-based solution, the need for implementation on commercially available remote manipulators would require separate high speed data acquisition and the ability to control high bandwidth auxiliary actuators. Not only was this approach outside of the cost and schedule of this project, it would also most likely produce tooling too expensive for cost-constrained D&D contractors to use. Another approach is to make use of a heuristic approach that recognizes tool chatter and modifies the manipulator trajectory to mitigate the chatter. This approach combines the heuristic approach along with elevating the voltages of the cutting tools to get the operating frequency as high as possible without destroying the tool.

The UTK RTSA system, shown in Fig. 9, uses multiple computers for operator interface, data acquisition, and control.[13] Manipulator control is done using a Linux-based PC running Real Time Innovations, Inc. ControlShell architecture. All control code is done in the ControlShell format and context using much of their established libraries. All real-time functions are located on this machine. The RTSA operator interface and sensor head data acquisition is done on a separate PC running Microsoft Windows.

Fig. 9. RTSA control station and computers.

After the operator identifies what is to be cut and establishes a planned script of the robot's intended execution path, a series of Cartesian points are generated defining the cut sequence trajectory. This Cartesian trajectory is then downloaded to the Linux-based real-time controller for execution. The real-time controller then converts the Cartesian trajectory into a joint space-based trajectory and executes that trajectory in a point-by-point timed sequence for the Schilling manipulator, shown in Figs. 10 and 11. The proposed chatter compensator for this effort needs to exist in the same ControlShell module that executes the Cartesian to joint space conversion and trajectory sequencing. The basic premise will be to interrupt the trajectory when the chatter module detects chatter, to maintain that interruption until chatter has dissipated, and then to slowly return to the desired trajectory (position and rate of motion). This will be done by modifying the ControlShell module's timing mechanism that is responsible for sequencing the trajectory points. The chatter decision for the time being will be a yes/no "binary" decision based on the output from the chatter detection module's variance ratio calculations.

Fig. 10. Schilling manipulator and test stand.

Fig. 11. Manipulator and tool stand.

IV. CONCLUSION

The original intent had been to have all development and testing complete at the time of this writing; however funding of technology development activities was eliminated by the Department of Energy's Environmental

Management office greatly slowing project execution. UTK has also had implementation problems with their Linux-based computer which delayed project execution. Testing has therefore not been possible to date. In summary, a background literature survey pointed to chatter detection using the ratio of variances of low and high frequency accelerometer signals generated by the saw during cutting. Prototype chatter detection software was developed based on this concept using standard digital signal processing techniques implementing low and high pass filters. The necessary device drivers were incorporated to interface the analog input board to the Linux-based computer. Final development and implementation of the control software is in progress. Testing and debugging of the approach and collection of the experimental data will be executed in the near future.

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