design uses only three multipliers per tap. Notice that a complex product $R+j\cdot I=(x+j\cdot y)(c+j\cdot s)$ can be computed with only three multipliers if $Z=c\cdot(X-Y)$ is computed first. Thus, $R=(c-s)\cdot Y+Z$ and $I=(c+s)\cdot X-Z$. The proposed index-based QRNS filter requires only two modular multiplications per tap that are easily computed by means of modulo adders. Table 2 shows implementation data for three and four multiplier-per-tap 2C complex FIR filters as well as for the proposed index arithmetic QRNS complex FIR filter. It provides the number of LEs, the operating frequency and the moduli selected to ensure the dynamic range. Results show that the proposed filter dramatically reduces the complexity of the system and provides a throughput advantage of about 60%.

Table 2: Resource reduction and speed-up achieved by complex FIR filter built in RNS-FPL technology

N	2C: 4/3 multiplier per coefficient		Proposed RNS-based complex FIR				
	LEs	F, MHz	LEs	Resource reduction, %	F, MHz	Speed-up, %	Moduli
4	7357 5984	83 85	7958	−8 −33	140.38	68 65	13, 17, 29, 37, 41, 53, 61
8	14651 11787	78 85	12104	17 −3	134.80	73 59	5, 13, 17, 29, 37, 41, 53, 61
16	29269 23559	74 79	20186	31 14	125.7	70 59.11	5, 13, 17, 29, 37, 41, 53, 61
32	58571 47056	–	35774	39 24	–	–	5, 13, 17, 29, 37, 41, 53, 61

Conclusion: We have provided benchmarks for programmable FIR filters built in RNS-FPL technology. Index arithmetic and the QRNS together with a selection of a small wordwidth modulus set were the keys for attaining low complexity and high throughput. RNS-FPL merged FIR filters were about 65% faster than 2C designs and required fewer logic elements in most cases. An index arithmetic QRNS-based complex FIR filter yielded better results. This filter was up to 60% faster than the three-multiplier-per-tap filter and required fewer LEs for filters having more than eight taps. In particular, a 32-tap filter required 24% less LEs than the classical design.

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Extended output injection and output feedback input–output linearisation

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An extended output injection problem is formulated for a single input, single output (SISO) nonlinear system, and an algorithm is proposed to solve the extended output injection problem. New results are then obtained for the solvability of dynamic output feedback input–output linearisation of an SISO nonlinear system.

Introduction: The problem of linearisation via output injections was first proposed to design an observer for nonlinear systems. Research has continued in two directions. In the first direction, development of algorithmic procedures and generalisations were made for analytic procedures, for multiple input, multiple output (MIMO) cases, for input-derivative-dependent output injections, for a block triangular observer normal form and for bilinearisation by output injections (see [1] and references therein). In the second direction, the first attempt for nonlinear systems is probably [2] when the output injection problem was linked with the problem of dynamic output feedback input–output (I/O) linearisation. The same ideas were extended to dynamic output feedback adaptive controller design in [3], and dynamic output feedback disturbance decoupling design in [4].

In this Letter, an extended output injection problem is formulated within the algebraic framework [5], and an algorithm is proposed to solve the extended output injection problem. As an application, new results are presented for the solvability of dynamic output feedback I/O linearisation of a nonlinear system. An example is included to show that the new results cover systems not covered by previous results.

Extended output injection algorithm: Consider a single input, single output (SISO) nonlinear system

$$\dot{x}=f(x,u)\qquad y=h(x)\tag{1}$$

where $x\in R^n$, $f(x)$, $g(x)$ and $h(x)$ are meromorphic functions.

Working in the algebraic framework [5], assume that the system is observable and satisfies that $\dim E^n=2n$ in which $E^k=\mathrm{span}\{\mathrm{d}y,\mathrm{d}u,\mathrm{d}\dot{y},\mathrm{d}\dot{u},\ldots,\mathrm{d}y^{(k-1)},\mathrm{d}u^{(k-1)}\}$.

The problem is formulated as: for $\omega\in E^n$, find, if possible, function $\phi_1(y,u)$, $\phi_2(z_1,y,u),\ldots,\phi_n(z_{n-1},\ldots,z_1,y,u)$ such that

$$\omega=\mathrm{span}\{\mathrm{d}[\phi_n(\cdot,\dot{\phi}_{n-2},\ldots,\dot{\phi}_1,y,u)\circ\cdots\circ\mathrm{d}\phi_2(\cdot,y,u)/\mathrm{d}t\circ\mathrm{d}\phi_1(y,u)/\mathrm{d}t]\}$$

in which it is assumed that $\partial\phi_1/\partial u\neq 0$ or $\partial\phi_1/\partial y\neq 0$. If the problem is solvable, then ω is called to admit extended output injections.

The original linearisation problem via output injections is obviously a special case of the above problem.

Extended output injection algorithm:

Step 1. Check 1.1: $\omega\in E^n$. If no, stop! Pick functions $\xi_1,\theta_1\in\mathcal{K}$ such that $\omega-\xi_1\mathrm{d}y^{(n-1)}-\theta_1\mathrm{d}u^{(n-1)}\in E^{n-1}$. Define a differential one-form $\bar{\omega}_1$ as $\bar{\omega}_1=\xi_1\mathrm{d}y+\theta_1\mathrm{d}u$. Check 1.2: $\mathrm{d}\bar{\omega}_1\Lambda\bar{\omega}_1=0$. If no, stop! Let $\phi_1(y,u)$ be such that $\bar{\omega}_1=\lambda_1\mathrm{d}\phi_1$ in which $\lambda_1\in\mathcal{K}$. Denote $z_1=\phi_1(y,u)$.

Step l ($l\leq n-1$). Check l.1: $\omega\in E^{n-l+1}+\mathrm{span}\{\mathrm{d}z_1^{(n-1)},\ldots,\mathrm{d}z_{l-1}^{(n-l)}\}$. If no, stop! Pick functions $\xi_l,\theta_l,\mu_{l,1},\ldots,\mu_{l,l-1}\in\mathcal{K}$ such that $\omega-\mu_{l,1}\mathrm{d}z_1^{(n-l)}-\cdots-\mu_{l,l-1}\mathrm{d}z_{l-1}^{(n-l)}-\xi_l\mathrm{d}y^{(n-l)}-\theta_l\mathrm{d}u^{(n-l)}\in E^{n-l}$. Define a differential one-form $\bar{\omega}_l$ as $\bar{\omega}_l=\mu_{l,l-1}\mathrm{d}z_{l-1}+\cdots+\mu_{l,1}\mathrm{d}z_1+\xi_l\mathrm{d}y+\theta_l\mathrm{d}u$. Defining the co-space $\Omega_l=\mathrm{span}\{\sum_{i=1}^{k-1}\partial\phi_k/\partial\dot{z}_i\mathrm{d}z_i,\ k=1,\ldots,\min(l-1,n-l);\ \mathrm{d}\phi_1\}$. Check l.2: $\dim(\mathrm{span}\{\bar{\omega}_l\}+\Omega_l)^*\geq\dim\Omega_l^*+1$. If no, stop! There exist $\pi_l\in\Omega_l$, $\lambda_l\in\mathcal{K}$ and $\phi_l(z_1,,z_{l-1},y,u)$ such that $\bar{\omega}_l+\pi_l=\lambda_l\mathrm{d}\phi_l$. Denote $z_l=\phi_l(z_{l-1},\ldots,z_1y,u)$.

Step n. Check n.1: $\omega\in E^1+\mathrm{span}\{\mathrm{d}z_1,\ldots,\mathrm{d}z_{n-1}\}$. If no, stop! Pick functions $\xi_n,\theta_n,\mu_{n,1},\ldots,\mu_{n,n-1}\in\mathcal{K}$ such that $\omega=\mu_{n,n-1}\mathrm{d}z_{n-1}+\cdots+\mu_{n,1}\mathrm{d}z_1+\xi_n\mathrm{d}y+\theta_n\mathrm{d}u$. Check n.2: $\mathrm{d}\omega\Lambda\omega=0$. If no, stop! End of algorithm.

Theorem 1: ω admits extended output injections if and only if it passes all the checks in the above algorithm.

Proof: Sufficiency is clear from the construction of the algorithm, because at the end of Step n, $d\omega \Lambda \omega = 0$.

Necessity is proved by mathematical induction. The necessity of passing the initial check and the two checks in Step 1 is obvious. Assume that it passes all the checks for Step $1, \dots, l$, $l \leq n-2$ we prove that it also passes the two checks in Step $l+1$. Let $z_i = \dot{\phi}_i(z_{i-1}, \dots, z_1, y, u)$, for $i = 1, \dots, l$. Then by assumption, $\omega \in \mathrm{span}\{d\phi_{n-1}, d\phi_{l+1}, dz_l, dz_1, dy, du\}$. Since $d\phi_{l+1} \subset \mathrm{span}\{dz_l, \dots, dz_1, dy, du\}$, so $d\dot{\phi}_{l+1} \subset \mathrm{span}\{d\dot{z}_l, \dots, d\dot{z}_1, d\dot{y}, d\dot{u}, dz_l, \dots, dz_1, dy, du\}$.

Similarly, it can be proved that $d\phi_{n-1} \subset \mathrm{span}\{dy, \dots, dy^{(n-l-2)}, du, \dots, du^{(n-l-2)}, dz_i, \dots, dz_i^{(n-l-2)}, i = 1, \dots, l\}$, and

$$d\dot{\phi}_{n-1} \subset \mathrm{span}\{dy, \dots, dy^{(n-l-1)}, du, \dots, du^{(n-l-1)}, dz_i, \dots, dz_i^{(n-l-1)}, 1 \leq i \leq l\} \quad (2)$$

Thus from the derivations above (2),

$$\omega \in E^{n-l} + \mathrm{span}\{dz_i, \dots, dz_i^{(n-l-1)}\} \quad (3)$$

A mathematical induction argument shows that, for $i = 1, \dots$, $\mathrm{span}\{dz_i, \dots, dz_i^{(k)}\} \subset E^{i+k}$, $\mathrm{span}\{dz_i, \dots, dz_i^{(n-l-2)}\} \subset E^{n-l-1} + \mathrm{span}\{dz_j^{(n-l-1)}, 1 \leq j \leq i-1\}$.

Only the latter is proved for illustration. In fact, it holds obviously for $i = 1$ because of the definition of z_1. Suppose now it holds for $i-1$. Since

$$\begin{aligned}\mathrm{span}\{dz_i, \dots, dz_i^{(n-l-2)}\} &\subset E^{n-l-1} + \mathrm{span}\{dz_j, \dots, dz_j^{(n-l-1)}, j = 1, \dots, i-1\} \\ &\subset E^{n-l-1} + \mathrm{span}\{dz_j^{(n-l-1)}, j = 1, \dots, i-1\}\end{aligned} \quad (4)$$

in which the second inclusion is due to the induction assumption, so it holds for i.

Combining (3) and (4), we see that $\omega \in E^{n-l} + \mathrm{span}\{dz_j^{(n-l-1)}, j = 1, \dots, i-1\}$, i.e. it is necessary to pass the first Check at Step $l+1$.

To prove the necessity of passing the second check of Step $l+1$, start with a more detailed expansion obtained by the definition of z_i, one has, for some $\xi \in \mathcal{K}$,

$$\omega - \xi \cdot \left(\sum_{i=1}^{l} \frac{\partial \phi_{l+1}}{\partial z_i} dz_i^{(n-l-1)} + \frac{\partial \phi_{l+1}}{\partial y} dy^{(n-l-1)} + \frac{\partial \phi_{l+1}}{\partial u} du^{(n-l-1)} \right) \in E^{n-l-1} + \mathrm{span}\{dz_i^j, 1 \leq i \leq \min(l, n-l+1); n-l-i-1 \leq j \leq n-l-2\} \quad (5)$$

One proves, again by mathematical induction, that there exist $\mu_{kij} \in \mathcal{K}$ such that,

$$dz_k^{(n-l-k-1)} = \mu_{k11} \left(\frac{\partial \phi_1}{\partial y} dy^{(n-l-1)} + \frac{\partial \phi_1}{\partial u} du^{(n-l-1)} \right) (\mathrm{mod}\, E^{n-l-1}), \dots,$$

$$\begin{aligned}dz_k^{(n-l-2)} &= \sum_{i=1}^{k-1} \frac{\partial \phi_k}{\partial z_i} dz_i^{(n-l-1)} + \mu_{kk1} \sum_{i=1}^{k-2} \frac{\partial \phi_{k-1}}{\partial z_i} dz_i^{(n-l-1)} + \cdots \\ &+ \mu_{kk(k-1)} \frac{\partial \phi_2}{\partial z_1} dz_1^{(n-l-1)} \\ &+ \mu_{k21} \left(\frac{\partial \phi_1}{\partial y} dy^{(n-l-1)} + \frac{\partial \phi_1}{\partial u} du^{(n-l-1)} \right) (\mathrm{mod}\, E^{n-l-1})\end{aligned} \quad (6)$$

Defining the co-space $\Omega_{l+1} = \mathrm{span}\{\sum_{i=1}^{k-1} \partial\phi_k/\partial z_i dz_i, \ k = 2, \dots, \min(l, n-l-1); \ \partial\phi_1/\partial y dy + \partial\phi_1/\partial u du\}$, and from the construction of the differential one-form $\bar{\omega}_{l+1}$ at Step $l+1$ of the algorithm, the expansion (5) to (6), one concludes that there is a differential one form $\pi_{l+1} \in \Omega_{l+1}$ such that $\bar{\omega}_{l+1} - \pi_{l+1} = \bar{\xi} d\phi_{l+1}$.

Hence, from Lemma 2.6 of [6], the second check in Step $l+1$ has to be passed.

Now assume that it passes all the checks in Step 1 to Step $n-1$, the necessity of passing the two checks in Step n can be similarly verified. ■

I/O linearisation by dynamic output feedback: Consider an SISO nonlinear system (1), it is said to be I/O linearisable by dynamic output feedback if there exists a dynamic output feedback $u = H(y, \eta, v)$, $\dot{\eta} = F(y, \eta, v)$ such that the closed loop system is diffeomorphic to $\dot{\zeta}^1 = A\zeta^1 + bv$, $\dot{\zeta}^2 = \bar{f}^2(\zeta, \eta, v)$, $y = c\zeta^1$, in which $\eta \in \mathbb{R}^q$, $\zeta^1 \in \mathbb{R}^{\bar{n}}$, $\zeta^2 \in \mathbb{R}^{n+q-\bar{n}}$, (c, A) is an observable pair.

Theorem 2: System (1) is input–output linearisable by dynamic output feedback if $\exists \tilde{n}, q \in \mathbb{N}$ such that

$$\begin{aligned}dy^{(\tilde{n})} &= \lambda_1 dy^{(\tilde{n}-1)} + \cdots + \lambda_{\tilde{n}} dy \\ &+ d[\phi_1(\cdot, \dot{\phi}_{q-2}, \dots, \dot{\phi}_1, y, u) \\ &\circ \cdots \circ d\phi_2(\cdot, y, u)/dt \circ d\phi_1(y, u)/dt]\end{aligned} \quad (7)$$

where $\partial\phi_1/\partial u \neq 0$, and $\lambda_i \in \mathbb{R}$ $(i = 1, \dots, \tilde{n})$. ■

Remark: Since the observability index cannot decrease $\tilde{n} \geq \bar{n}$ and since the relative degree cannot decrease $\tilde{n} - q + 1 \geq r$.

Proof of Theorem 2: Consider system (1). Set, for $i = 1, \dots, q-1$, $\eta_i = \phi_i(\dot{\eta}_{i-1}, \dots, \dot{\eta}_1, y, u)$, $v = \phi_q(\dot{\eta}_{q-1}, \dots, \dot{\eta}_1, y, u)$. Note that from the definition of the relative degree, ϕ_1 is invertible w.r.t. u and ϕ_i is invertible w.r.t. $\dot{\phi}_{i-1}$, for $i = 1, \dots, q$. Define the following dynamic compensator $u = \phi_1^{-1}(y, \eta_1)$, $\dot{\eta}_i = \phi_{i+1}^{-1}(\eta_{i+1}, \phi_i^{-1}, \dots, \phi_2^{-1}, y, \phi_1^{-1}(y, \eta_1))$, for $i = 1, \dots, q-2$, and $\dot{\eta}_{q-1} = \phi_q^{-1}(v, \phi_{q-1}^{-1}, \dots, \phi_2^{-1}, y, \phi_1^{-1}(y, \eta_1))$, the closed-loop system has the I/O relationship: $dy^{(\tilde{n})} = \lambda_1 dy^{(\tilde{n}-1)} + \cdots + \lambda_{\tilde{n}} dy + dv$. Thus, system (1) is I/O linearised by dynamic output feedback. ■

To check the condition, first check: $\exists \alpha_1, \dots, \alpha_{\tilde{n}-q} \in \mathbb{R}$ such that $dy^{(\tilde{n})} - \alpha_1 dy^{(\tilde{n}-1)} - \cdots - \alpha_{\tilde{n}-q} dy^{(q-1)} \in E^q$. If yes, then denote $\omega = dy^{(\tilde{n})} - \alpha_1 dy^{(\tilde{n}-1)} - \cdots - \alpha_{\tilde{n}-q} dy^{(q-1)}$. If ω passes checks of the extended output injection algorithm, then an I/O linearisable dynamic output feedback can be designed.

Example: Consider the system $\dot{x}_1 = x_2 - 1/2 \ln(x_1 + 2u)$, $\dot{x}_2 = (x_1 + u)/(x_1 + 2u) + 1/2((x_2 - 1/2 \ln(x_1 + 2u))/(x_1 + 2u))$, $y = x_1$. It can be verified that the conditions given in [2] and [7] are not satisfied. The input–output equation can be derived as $\ddot{y} = (y + u - \dot{u})(y + 2u)$. Going through the extended output injection algorithm, one sees that $\ddot{y}$ admits extended output injections, $\phi_1(y, u) = u$ and $\phi_2(w, y, u) = (y + u - w)/(y + 2u)$. The system is I/O linearisable by the following dynamic output feedback: $u = \eta$, $\dot{\eta} = \eta + y + (y + 2\eta)v$.

Conclusion: An extended output injection problem was proposed for SISO nonlinear systems in the algebraic framework [5]. An extended output injection algorithm was presented to solve the problem. Application of the results obtained was made to the I/O linearisation problem of SISO nonlinear systems. New sufficient conditions were found.

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Measurements of SAW and pseudo SAW in $GdCa_4O(BO_3)_3$ crystal

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The surface acoustic wave (SAW) and pseudo SAW parameters in the $GdCa_4O(BO_3)_3$ crystal were measured for the first time. For SAW, the largest electromechanical coupling coefficient of about 0.3% and a velocity of 3215 m/s were obtained for the *ZX* orientation, while for the pseudo SAW, the above parameters were about 1.3% and 3591 m/s, respectively, for the *XY* orientation.

Introduction: Recently, new series of rare earth calcium oxyborates with chemical formula $RCa_4O(BO_3)_3$ (R = Gd, Y, La and Nd) were grown into single crystals. These crystals can be used for optical second-harmonic generation and laser self-frequency doubling [1]. Some of the effective elastic, piezoelectric and dielectric constants of the $GdCa_4O(BO_3)_3$ crystal were also measured recently [2]. The crystal belongs to the monoclinic *m* point group. In this case, the *X*, *Y*, *Z* axes of the rectangular coordinate system should be related to the *b* and *c* crystallographic axes as follows: $b \| Y$, $c \| Z$, and the *X* axis is perpendicular to the *Y* and *Z* axes and forms the right-handed system [3]. In this Letter, the measured surface acoustic wave (SAW) and pseudo SAW properties of the crystal are presented for the first time.

Experimental method and measurement results: The $GdCa_4O(BO_3)_3$ crystals were grown by the Czochralski method [4]. The synthesised charge was melted in iridium crucible and the seed along the *b* axis was introduced into the crucible. The growth process was computer monitored by a weight-and-diameter system. A nitrogen atmosphere was provided during the growth. The typical growth rate was about 1 mm/h and the crystal was rotated at 25 rpm. The resulting crystals were colourless, with good optical quality. The size of the crystals without macroscopic defects and crackings was about 25 mm in diameter and 50 mm in length. Wafers polished on one side were then manufactured for the *X*, *Y* and *Z* cuts.

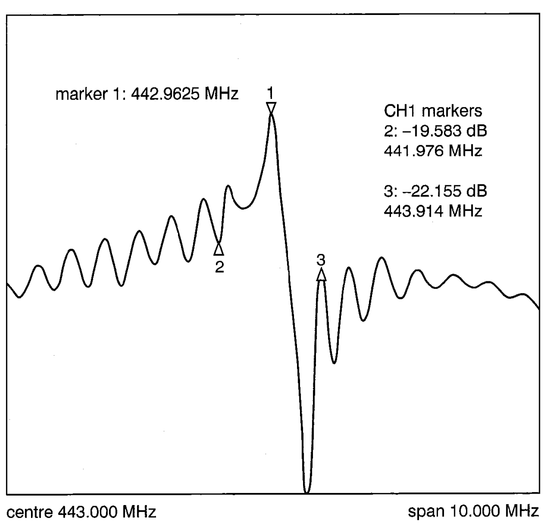

Fig. 1 *Measured amplitude response of resonator for ZX orientation*

The SAW and pseudo SAW (PSAW) parameters were determined by the method of matching the measured and calculated amplitude responses of the synchronous two-port resonator [5]. Since the available crystal substrates were small, the structure of the resonator designed for the frequency 433.92 MHz on the ST-cut quartz [6], was used for the measurements. The resonators were fabricated by the lift-off method and aluminium was used as a metal for the electrodes (about 70 nm thick). The resonators were mounted in the TO-39 metal packages and measured in the 50 Ω measuring system (Agilent Network Analyser Type 8753T). As an example, the measured amplitude response of a resonator fabricated on the *ZX* orientation is shown in Fig. 1. For some orientations, both SAW and PSAW were found. The measured SAW and PSAW parameters are shown in Table 1. The first letter of the orientation indicates the plane, and the second letter indicates the direction of SAW and PSAW propagation. The relative dielectric constant ε_r for each orientation was determined by comparing the measured and calculated static capacitances of the interdigital transducer (IDT). The velocity v in the area of periodical electrodes and the electromechanical coupling coefficient K^2 were determined by matching the measured and calculated amplitude responses of the resonator for each orientation [5]. Temperature coefficient of time delay (TCD) was measured for the three most interesting orientations.

Table 1: SAW and PSAW parameters in $GdCa_4O(BO_3)_3$ crystal

Orientations	*XY*		*XZ*	*YX*	*YZ*		*ZX*
ε_r	10.5		10.5	11.5	10.5		10.4
Parameters	SAW	PSAW	SAW	PSAW	SAW	PSAW	SAW
v [m/s]	2745	3591	3214	3504	2667	3483	3215
K^2 [%]	0.05	1.3	0.24	0.5	0.064	0.13	0.3
TCD [ppm/K]	–	50	80	–	–	–	80

Conclusion: Preliminary measurements of SAW and PSAW in the $GdCa_4O(BO_3)_3$ crystal are presented for the first time. For SAW, the largest K^2 was obtained for the *ZX* orientation, and for PSAW for the *XY* orientation. The *XZ* and *ZX* orientations for SAW may find applications in temperature sensors since they have much larger TCD than that of *YX* orientation in quartz (−24 ppm/K) [7]. For PSAW, the largest K^2 was obtained for the *XY* orientation. This PSAW may find applications in bandpass filters. More complete characterisation of the crystal will be possible when all the elastic, piezoelectric and dielectric constants are known, since the SAW and PSAW parameters can then be theoretically predicted.

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